LTER-Belgium

Results of long-term, large-scale and intensive monitoring at the Flemish forest condition monitoring sites within the LTER-Belgium network

Nathalie Cools, Arne Verstraeten, Geert Sioen, Johan Neirynck, Peter Roskams, Gerald Louette, Maurice Hoffmann

INSTITUUT
NATUUR- EN BOSONDERZOEK

Auteurs:
Nathalie Cools, Arne Verstraeten, Geert Sioen, Johan Neirynck, Peter Roskams, Gerald Louette, Maurice Hoffmann
Instituut voor Natuur- en Bosonderzoek

Het Instituut voor Natuur- en Bosonderzoek (INBO) is het Vlaams onderzoeks- en kenniscentrum voor natuur en het duurzame beheer en gebruik ervan. Het INBO verricht onderzoek en levert kennis aan al wie het beleid voorbereidt, uitvoert of erin geïnteresseerd is.

Vestiging:
INBO Geraardsbergen
Gaverstraat 35, 9500 Geraardsbergen
www.inbo.be

e-mail:
nathalie.cools@inbo.be

Wijze van citeren:
Cools, N., Verstraeten A., Sioen G., Neirynck J., Roskams P., Louette G., Hoffmann M. (2016). LTER-Belgium - Results of long-term, large-scale and intensive monitoring at the Flemish forest condition monitoring sites within the LTER-Belgium network. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2016 (INBO.R.2016.11433903). Instituut voor Natuur- en Bosonderzoek, Brussel.

D/2016/3241/014
INBO.R.2016.11433903
ISSN: 1782-9054

Verantwoordelijke uitgever:
Maurice Hoffmann

Druk:
Managementondersteunende Diensten van de Vlaamse overheid

Foto cover:
Foliar sampling at intensive forest monitoring site (Luc De Geest)

LTER-Belgium

Results of long-term, large-scale and intensive monitoring at the Flemish forest condition monitoring sites within the LTER-Belgium network

Nathalie Cools, Arne Verstraeten, Geert Sioen, Johan Neirynck, Peter Roskams, Gerald Louette, Maurice Hoffmann

INBO.R.2016.11433903
D/2016/3241/014

RESEARCH INSTITUTE
NATURE AND FOREST

Summary

LTER-Belgium stands for “Long-Term Ecosystem Research Network in Belgium”. The kick-off of the LTER-Belgium network was given at the official recognition by the International Long-term Ecological Research (ILTER) network (annual meeting December 2014 in Ancud, Chiloe Island, Chile). The Belgian proposal included initially five forest sites, each of which contains an intensive monitoring plot for forest condition, one coastal sand dune landscape, one heathland landscape, one brook-heathland-bog landscape, and the Floodplain landscape of the Valley of the Dyle river. Furthermore, it contained three Long-Term Socio-Ecological Research platforms: the Scheldt Estuary and its alluvial plains, the Belgian coastal waters and sand bank systems, and the National Park De Hoge Kempen. At the beginning of 2016, LTER-Belgium comprised 27 sites and 5 platforms and was still growing. This report starts with a very brief overview of the Belgian network at the time of the publication.

As the intensive forest monitoring programme for which data have been collected for more than 20 years, forms a substantial part of the long-term ecosystem research conducted within the Belgian network, this first LTER-Belgium focuses, as a case study, on the main trends, research results and insights obtained from this forest condition monitoring programme. This programme is part of the International Co-operative Programme on Assessement and Monitoring of Air pollution Effects on Forests (ICP Forests) of the UNECE Convention on Long-Range Transboundary Air Pollution. ICP Forests monitors the forest condition at two monitoring intensity levels: The Level I monitoring is based on around 6000 observation plots on a systematic transnational grid of 16 x 16 km throughout Europe to gain insight into the geographic and temporal variations in forest condition while the Level II intensive monitoring comprises around 500 plots in selected forest ecosystems with the aim to clarify cause-effect relationships.

The intensive forest monitoring (Level II) network in Flanders consists of 5 core plots and 6 additional plots. Samples of atmospheric deposition and soil solution are collected biweekly in order to determine the concentrations of nutrients and pollutants. Atmospheric depositions below canopy (throughfall + stemflow) of SO_4^{2-} decreased with 0.05–0.07 $kmol_c\ ha^{-1}\ y^{-1}$ at the 5 Level II core plots over 20 years (1994-2014). Depositions of NH_4^+ decreased with 0.04–0.07 $kmol_c\ ha^{-1}\ y^{-1}$ at the five plots, while NO_3^- depositions decreased only at three plots, with 0.005−0.01 $kmol_c\ ha^{-1}\ y^{-1}$. The decrease in acidifying and eutrophicating depositions resulted in initial chemical recovery of the soil solution, evidenced by decreasing trends in SO_4^{2-} and NO_3^- concentrations and – particularly during the last 10 years of the monitoring period − increasing trends in soil solution pH. The acid neutralizing capacity (ANC) increased but remained negative at most depths in most plots, indicating that soil acidification is slowing down. On the other hand, the soil solution Bc:Al ratio is below the critical limits for damage to fine roots and is further declining in four plots, because uptake and leaching of base cations are not entirely compensated by mineral weathering and deposition. Foliar nutrient concentrations of the main tree species in the 5 Level II core plots are analysed biannually, in order to describe the nutritional status of the trees and to assess changes in tree nutrition. Nitrogen is one of the key elements in plant nutrition. Decades of high atmospheric N deposition in Flanders have resulted in a considerable N enrichment. In 1995-2013 the foliar N concentrations in all of the investigated tree species (*Fagus sylvatica*, *Quercus robur*, *Pinus sylvestris*, *Pinus nigra*) were high, indicating luxury consumption of N.

In addition to the Level II-monitoring, long-term measurements of air pollutants and meteorological variables have been conducted at the flux measurement tower at Brasschaat since 1995. The air pollution characteristics at this site are typical for a suburban forest exposed to vehicle emission (NO_x), which is strongly affecting the NO-NO_2-O_3 chemistry. The site is, additionally, located in the waste plume derived from stack emissions (SO_2, NO_x, black carbon) generated by the petrochemical refinery in Antwerp port. Although no important agricultural emission sources are present in close proximity to the site, ammonia levels are elevated when winds blow from the eastern wind sector (due to remote agricultural activities > 5 km). Air pollution concentrations of SO_2 and NO_x show declining trends, whereas ozone levels tend to increase, especially during the spring time. Annual concentrations of NO_x and NH_3 still exceed long-term critical levels to protect vegetation from adverse effects. Also ozone indices, calculated to judge the risk for ozone damage, exceed the critical levels for ozone exposure. The meteorological variables, which are collected on a half-hour basis, are used for dry deposition calculations and scrutinizing the environmental controls on the pollutant concentrations and the canopy uptake.

While the European crown condition survey (Level I) is developed on a 16 x 16 km grid, the Flemish crown condition survey is densified to a 4 x 4 km grid, with 72 regional plots. In 2014 21.1% of the sample trees showed more than 25% defoliation. The overall average defoliation was 23.4%. *Q. robur*, *Populus* sp., *P. nigra* and the trees in the category ‘other broadleaves’ showed the worst crown condition in this large-scale survey. The mean defoliation of all species together shows a slight decrease between 1995 and 2008. After 2008 there is a deterioration in crown condition that continues till 2012. In 2013 and 2014 crown condition is recovering but the mean defoliation remains high. The condition of *Q. robur* shows similar trends. From 2009 to 2012 there is an important increase in defoliation. Both mean defoliation and the share of trees considered as damaged are increasing for 4 consecutive

years. After 2012 crown condition is improving but the defoliation remains at a high level. The crown condition of *F. sylvatica* fluctuates radomly over time, but this species reveals a better crown condition compared to *Q. robur*. *P. sylvestris* shows a decrease in defoliation, with a remarkable improvement of the crown condition from 2000 to 2009. The Level I network is not a part of LTER-Belgium, but the findings can be used to evaluate results of the Level II monitoring in a wider spatial context.

The results from the Level I and Level II networks and the measuring tower illustrate well that long-term field observations at parallel sites, made with a sufficiently high frequency provide a powerful tool to study the trends in and the effects of long-term air pollution on the forest ecosystem. The time series provide extremely valuable information for scientists, forest managers and policy makers.

In the final chapter, an overview is given of present and future data evaluations on forest condition at the Flemish, national (Belgium) and international level.

Acknowledgments

We greatly acknowledge the contribution of numerous individuals involved in the forest monitoring project in sample collection, analysis of samples and interpretation of results since 1987. Data collection has been funded by the Ministry of the Flemish Community and the Flemish Government (1987 – present). Part of this work was based on monitoring co-financed by the European Commission under regulations (EC) No 3528/86, Forest Focus (EC) No 2152/2003 for data from 2005 and 2006, FutMon (EC) LIFE07 ENV/D/218 for data from 2009 till June 2011.

Thanks to Kris Vandekerkhove and Ann Milbau for internal reviewing.

Table of Contents

1 Context and framework

1.1 Structure of the report

Chapter 1 provides a brief summary of the LTER-Belgium network, its vision, mission and goals and present the network in terms of its sites and platforms.

Chapter 2 covers the main research results and insights from the long-term intensive forest monitoring programme running on the five permanent forest plots at five LTER-Belgium sites since the early nineties (Level II). It is a first case study that demonstrates the type of research that is running within the LTER-Belgium framework. The five plots belong to the network of the international cooperative programme (ICP Forests) operating under the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). ICP Forests is assessing and monitoring the effects of air pollution on forests since 1985. With its 30 years of experience, the programme gained a thorough insight into the geographical and temporal variations in forest condition throughout Europe and in the cause-effect relationships in selected forest ecosystems.

Chapter 3 presents results from the air quality survey at the measuring tower in Brasschaat, part of the master LTER-site 'De Inslag' (LTER_EU_BE_001). On this 40 m high measuring tower, INBO is monitoring meteorological variables and the concentration of air pollutants since 1995. Meteorological data include vertical profiles of air temperature and humidity, wind speed and direction, ingoing and outgoing shortwave and longwave radiation, rainfall and throughfall. Vertical profiles of SO_2, O_3 and NO_x concentrations are being measured at two inlets above the canopy (at 24 and 40 m). Ammonia (NH_3) air concentrations have been measured using Radiello passive samplers since 2009 (this was also done at the other four Level II plots). This chapter presents results for meteorological variables and concentrations of air pollutants, with particular attention for trends and seasonality. Air pollutant concentrations are also evaluated in relation to critical levels.

Chapter 4 contains the results of the large-scale forest condition monitoring (Level I) network in Flanders. Forest health monitoring started in Flanders in 1987. The European crown condition survey (Level I) is developed by means of a systematic grid of 16 x 16 km. In Flanders, the monitoring was originally conducted on an 8 x 8 km grid, with 41 monitoring plots. Originally 10 plots were part of the international 16 x 16 km Level I survey. From 1995 on the Level I survey was performed on a 4 x 4 km grid, with 72 regional plots. Defoliation is the main criterion used to assess the condition of the crowns. Trends for the last 20 years (1995−2014) of crown condition assessment are presented for Quercus robur, Fagus sylvatica and Pinus sylvestris.

In **Chapter 5** we list a number of future challenges for LTER-Belgium and suggest a number of research opportunities at different spatial scales.

1.2 The LTER-Belgium network

LTER-Belgium stands for the "Long-Term Ecosystem Research Network in Belgium". The kick-off of the LTER-Belgium network was given at the official recognition by the International Long-term Ecological Research (ILTER) network (annual meeting December 2014). By becoming member of ILTER, LTER-Belgium joined simultaneously the LTER-Europe network. LTER-Europe (www.lter-europe.net) is closely associated with ALTER-Net (www.alter-net.info), the organisation through which LTER-Europe was established and institutionalized.

LTER-Belgium is a network of sites engaged in long-term, site-based ecological and socio-ecological research, with following typical characteristics:
(1) **Site-based research** – LTER-Belgium is a national network carrying regular monitoring and research of broad spectrum of environmental variables at a local level (LTER Sites) and of environmental as well as socio-ecological variables at a sub-regional level (LTSER-platforms) that continuously feeds scientific analyses, up-scaling, synthesis and theory development.
(2) **Long term** – LTER-Belgium dedicates itself to consistent research and monitoring with the time horizon of decades. This produces a particular type of science, which requires its own statistics, tools and produce unique results.
(3) **System approach** – a target of LTER-Belgium research is to better understand complexity of ecological and socio-ecological systems, dynamics of abiotic and biotic variables, role and dynamics of system components, and interrelations between them.

(4) **Process-oriented research** – tracing dynamics of interactions between different components of socio-ecological systems LTER-Belgium aims at understanding complex cause-effect relationships and their dynamics in time.

LTER-Belgium meets the criteria for networks, sites and platforms of LTER-Europe and secures continuous monitoring and delivery of sound science based on the above mentioned LTER characteristics.

1.3 Vision, mission and goals of LTER-Belgium

LTER-Belgium's **vision** is a world in which science gives insight in environmental phenomena and helps to prevent and solve environmental and socio-ecological problems. LTER-Belgium aims to become the national reference network for cooperation in long term environmental scientific research in Belgium.

The **mission** of LTER-Belgium is to improve the understanding of the functioning of the ecosystems in Belgium in order to provide answers to current and future environmental issues, by facilitating and supporting national and international cooperation on long-term environmental research and monitoring.

To streamline the study on the interplay between the environment and the socio-economic activities, LTER Belgium adopts the DPSIR (Driving forces, Pressures, States, Impacts and Responses) framework. The DPSIR represents a system analysis view: social and economic developments (i.e. drivers such as demographic growth, technological developments,...), exert pressure (e.g. land use changes, climate change, eutrophication, acidification,...) on the environment and, as a consequence, the state of the environment changes (e.g. loss of biodiversity, loss of sustainability). This leads to impacts on e.g. human health, ecosystems and materials that may elicit a societal response that feeds back on the driving forces (e.g. national emission ceilings,...), on the pressures or on the state of the ecosystems (e.g. forest health condition) or impacts directly, through adaptation or curative action (e.g nature restoration). LTER-Belgium aims at long-term ecosystem research in order to understand the DPSIR cycle in ecosystem health including research on the intrinsic pattern and processes of the ecosystem.

LTER-Belgium's **goals** are to:

1. Foster collaboration and coordination among ecological researchers and research institutes at national and international scale in long-term ecosystem research.
2. Facilitate the generation, use, exchange and preservation both within and outside the country of long-term ecological and socio-ecological data from LTER-sites or LTSER-platforms in Belgium.
3. Deliver scientific information to scientists, policymakers, and the public to meet the needs of decision-makers at multiple levels.
4. Facilitate education of the next generation of long-term scientists.

1.4 Definitions

LTER-Belgium distinguishes LTER-sites and LTSER-platforms following the definitions set by LTER-Europe. An LTER site can be a simple or a complex site. Furthermore a distinction is made between master sites, regular sites and emerging or extensive sites.

1.4.1 LTER-site ('traditional' LTER-site)

A LTER-site ("traditional" LTER-site) is a LTER-facility of limited size (1ha-10 km²) representing one or more habitat types and forms of land use (e.g. forests, agro-pastoral areas, wetlands and rivers, urban and sub-urban areas,…) at one or more spatial locations and/or altitudes. A LTER-site can contain different field stations within the site (such as plots, grid points,…). Activities are concentrated on biogeochemical processes and selected taxonomic groups.

1.4.2 LTSER-platform

A LTSER-platform ("next generation" LTER-site, LTER-cluster, Multifunctional Research Platform) consists of a modular hierarchy of sub-sites (existing LTER facilities) covering different habitats, forms and intensities of land use, different types of management practices, different scales (local to landscape) and relevant infrastructures such as laboratories and instrumented catchments. The elements represent the main habitats, land use forms and practices relevant for the region (100-10,000 km²) and cover scales from local to landscape level. LTSER-platforms are economic and social units, or coincide/overlap with such units, where adequate information on land use history, economy and demography is available.

These platforms operate at the scale(s) and levels required to detect socio-environmental phenomena and manifest clearly defined problems on the interface between social and environmental dynamics. They provide a framework for interdisciplinary teams to undertake detailed qualitative and quantitative study of specific aspects of the dynamics of socio-environmental interaction, so that models can be developed which allow for up-scaling the knowledge involved.

The core characteristics of LTSER-platforms include:

- Multi-site (several LTER-sites included in one platform)
- Multi-habitat
- Scale consciousness (hierarchy of scales, multilevel analyses, up/down-scaling, ...)
- Social dimension, sustainable regional development, multi- and trans-disciplinarity
- Interoperability and congruency of data across disciplines
- Infrastructure for optimized multi-site-experiments
- Within LTER-Europe, the set of LTSER-platforms aim to cover the major socio-ecological regions of Europe, which cover the biogeographical regions and the socio-economic regions.
- Within an LTSER-platform the local gradients are to be covered such as the urban-natural gradient, habitat types, management practices, altitude etc.
- Focus: Processes (fast and slow, related to biodiversity and others), testing & validation of (biodiversity-) indicators (incl. link to models and theories)
- Link of research and monitoring, socio-economic and ecological research

1.4.3 Simple site

On a simple site one single ecosystem type is subject of the long-term ecosystem research.

1.4.4 Complex site

On a complex site more ecosystem types are observed and studied.

1.4.5 Master site

- A master site is a Highly instrumented & permanently operated site (HIS).
- The design of the site is based on an Ecosystem approach. So it is designed according to the ecological profile and enables integrated analyses across system strata (geosphere to atmosphere) and covering therefore the required spatial scales.
- A master site combines regular sampling (weekly as standard) and permanent measurements and inventories at appropriate intervals.
- Experimental approaches are existing or are possible.
- There is an all year round access and power supply to enable e.g. measurement of climate data according to international standards.
- There is a synergy with other networks and/or projects that use this category of site (e.g. EMEP, ICOS, UNECE ICPs, national monitoring networks, ...)
- The site is operational for at least 10 years.
- A master site can be flagged as a key ecosystem research infrastructure on European scale.

1.4.6 Regular site (R-site)

Regular sites comply with the description of Master LTER-sites, but differ in volume of instrumentation as well as multi use and availability of long-term data across all ecosystem compartments and disciplines.

1.4.7 Emerging or extensive site

This class represents EMERGING = recently established LTER-sites (3-5 years of observation) being developed towards a higher category or EXTENSIVE = LTER-sites with specific long-term monitoring and scientific foci and therefore not following the full ecosystem approach (e.g. for reasons of limited considered spatial scale). Extensive LTER-sites may emphasize the long-term monitoring (observation), but there must be an explicit research component.

1.5 The sites and platforms of LTER-Belgium

In 2014 the Belgian proposal included five forest sites, each of which contains an intensive monitoring plot for forest condition, one coastal sand dune landscape (Westhoek Coastal dunes), one heathland landscape (Heathland reserve De Zoom-Kalmthoutse Heide, a transboundary nature reserve), one brook-heathland-bog landscape (Valley of the Zwarte Beek), and the Floodplain landscape of the Valley of the Dyle river. Furthermore, three Long-Term Socio-Ecological Research platforms were proposed: the Scheldt Estuary and its alluvial plains, the Belgian coastal waters and sand bank systems, and the National Park De Hoge Kempen.

In 2015 and 2016 the network was further elaborated in number of sites, number of partners and in geographical extent. While the first proposal only included Flemish sites, the network anno 2016 became a real Belgian network with a more balanced representation of Flemish and Walloon sites and partners. LTER-Belgium comprises 27 sites and 5 platforms and is still growing (Figure 1 and **Fout! Verwijzingsbron niet gevonden.**). From the biogeographical point of view, 18 sites/platforms are situated in the Atlantic region and 14 in the Continental biogeographical region. The Research for Nature and Forest (INBO) is providing the LTER-site coordinators on 10 sites and 1 platform.

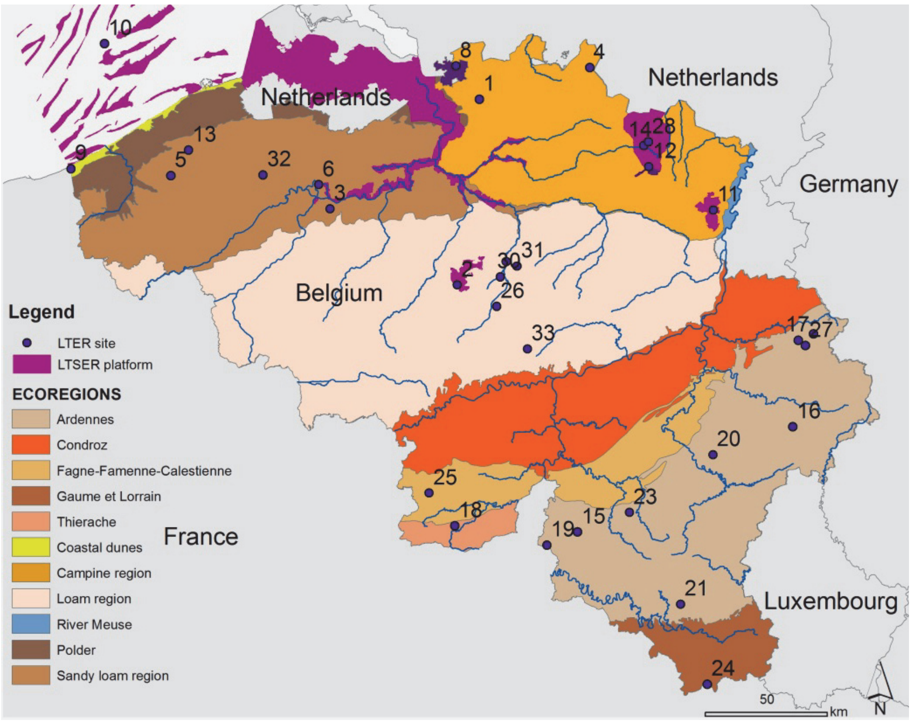

Figure 1 The LTER-Belgium network consisting of 27 LTER- sites and 5 LTSER-platforms (status June 2016).

Table 1 List of LTER-Belgium sites and platforms.

Name	Site Code	Site/platform	Cate-gorie	Size (ha)	Since	Dominant ecosystem type	Site coordinator	Institute
Brasschaat – De Inslag	LTER_EU_BE_001	Simple site	Master	2	1988	Temperate coniferous forests	Johan Neirynck	INBO
Zoniënwoud/Forêt de Soignes/Sonian Forest	LTER_EU_BE_02	LTSER-platform	Regular	4400	1988	Broadleaved deciduous woodland	Patrick Huvenne	ANB
Gontrode – Aelmoeseneie Forest	LTER_EU_BE_03	Simple site	Master	28.5	1988	Temperate broadleaf and mixed forests	Kris Verheyen	UGent
Ravels Forest	LTER_EU_BE_04	Simple site	Regular	0.5	1988	Temperate coniferous forests	Arne Verstraeten	INBO
Forest of Wijnendale	LTER_EU_BE_05	Simple site	Regular	200	1988	Broadleaved deciduous woodland	Kris Vandekerkhove	INBO
Scheldt Estuary and its alluvial plains	LTER_EU_BE_06	LTSER-platform	Emerging	140272	1991	Estuary	Gunther Van Ryckegem	INBO
Heathland reserve De Zoom-Kalmthoutse heide	LTER_EU_BE_08	Complex site	Extensive	4000	1975	Temperate grasslands, savannas, shrublands	Geert De Blust	INBO
Westhoek Coastal dunes	LTER_EU_BE_09	Simple site	Regular	340	1995	Coastal dune	Sam Provoost	INBO
Belgian coastal waters and sand bank systems	LTER_EU_BE_10	LTSER-platform	Regular	345400	2002	Temperate shelfs and seas	Klaas Deneudt	VLIZ
National Park Hoge Kempen	LTER_EU_BE_11	LTSER-platform	Emerging	5700	2006	Heathland, scrub and tundra	Natalie Beenaerts	UHasselt
Valley of the Zwarte Beek	LTER_EU_BE_12	Complex site	Emerging	800	1991	Temperate broadleaf and mixed forests	Piet De Becker	INBO
FORBIO Zedelgem	LTER_EU_BE_13	Simple Site	Emerging	9.5	2009	Temperate broadleaf and mixed forests	Kris Verheyen	UGent
FORBIO Hechtel-Eksel	LTER_EU_BE_14	Simple Site	Emerging	8	2012	Temperate broadleaf and mixed forests	Bart Muys	KULeuven
FORBIO Gedinne	LTER_EU_BE_15	Simple site	Emerging	9	2009	Temperate broadleaf and mixed forests	Quentin Ponette	UCL
Vielsalm	LTER_EU_BE_16	Simple site	Regular	2	1996	Temperate broadleaf and mixed forests	Caroline Vincke	UCL
Waroneu	LTER_EU_BE_17	Complex site	Regular	83	1991	Temperate coniferous forests	Monique Carnol	ULg
Baileux – La Sormone	LTER_EU_BE_18	Simple site	Regular	5	2001	Temperate broadleaf and mixed forests	Mathieu Jonard	UCL
Willerzie	LTER_EU_BE_19	Simple site	Regular	0.5	1995	Temperate coniferous forest	Quentin Ponette	UCL
Dochamps	LTER_EU_BE_20	Simple site	Regular	0.5	1995	Temperate coniferous forest	Quentin Ponette	UCL
Mellier	LTER_EU_BE_21	Simple site	Regular	0.5	1995	Temperate coniferous forest	Quentin Ponette	UCL
Baelen	LTER_EU_BE_22	Simple site	Regular	0.5	1995	Temperate broadleaf and mixed forests	Quentin Ponette	UCL
Tellin	LTER_EU_BE_23	Simple site	Regular	0.5	1995	Temperate broadleaf and mixed forests	Quentin Ponette	UCL
Ruette	LTER_EU_BE_24	Simple site	Regular	0.5	1995	Temperate broadleaf and mixed forests	Quentin Ponette	UCL
Chimay	LTER_EU_BE_25	Simple site	Regular	0.5	1995	Temperate broadleaf and mixed forests	Quentin Ponette	UCL
Louvain-la-Neuve	LTER_EU_BE_26	Simple site	Regular	0.5	1998	Temperate broadleaf and mixed forests	Quentin Ponette	UCL
La Robinette	LTER_EU_BE_27	Complex site	Regular	81	1991	Temperate coniferous forests	Monique Carnol	ULg
Bosland	LTER_EU_BE_28	LTSER-platform	Emerging	4000	2006	Temperate coniferous forests	Bart Tessens	ANB
Doode Bemde	LTER_EU_BE_29	Complex site	Regular	400	1998	Temperate grasslands, savannas, shrublands	Piet De Becker	INBO
Rode Forest	LTER_EU_BE_30	Complex site	Regular	90	1991	Temperate broadleaf and mixed forests	Kris Vandekerkhove	INBO
Meerdaal Forest	LTER_EU_BE_31	Complex site	Regular	635	1991	Broadleaved deciduous woodland	Beatrijs Van der Aa	INBO
Lake Kraenepoel	LTER_EU_BE_32	Simple site	Regular	22	1999	Small shallow lakes	Jo Packet	INBO
Lonzée	LTER_EU_BE_33	Simple site	Regular	11.8	2004	Agricultural cropland	Bernard Heinesch	ULg

The sites of Brasschaat − De Inslag (LTER_EU_BE_001), Sonian Forest (LTER_EU_BE_02), Gontrode − Aelmoeseneie Forest (LTER_EU_BE_03), Ravels Forest (LTER_EU_BE_04) and the Forest of Wijnendale (LTER_EU_BE_05) represent five forest ecosystems common in Northern Belgium. Each of this sites comprise an ICP Forests Level II plot though on the same sites a wide range of long-term ecological research activities are on-going.

The LTER site of **De Inslag** (**LTER_EU_BE_001**) is located in the community of **Brasschaat** in the northern Campine ecoregion of Flanders. This site consists of a fenced scientific area (2 ha) within a Scots pine forest, which contains a 40 m high measuring tower, where INBO is monitoring meteorological variables and the concentration of air pollutants since 1995 and contains a Level II monitoring plot. The scientific area and the surrounding forest also function as a Belgian ICOS measuring site (www.icos-belgium.be), which is coordinated by the Research Centre of Excellence PLECO (Plant and Vegetation Ecology) of the University of Antwerp (www.uantwerpen.be/en/rg/pleco).

The **Sonian Forest** (**LTER_EU_BE_02**) is a unique, large and centrally located forest, shortlisted as a potential UNESCO World Heritage Site, with an exceptionally high biodiversity and large tracts of old-growth forest. It has a long history of research across different disciplines and a well-documented archive of management data. Long-term ecological research in the 4400 ha forest covers the areas of biogeochemistry, soil science, geology, (urban) forestry, climate change, remote sensing, biodiversity and archaeology. It offers opportunities for multidisciplinary research which till now has not been fully explored. The ICP Forests monitoring plot in the Sonian Forest is located on the edge of a strict forest reserve where the dynamics of the forest ecosystem are monitored since the mid 1980's through the monitoring of the composition of the tree, shrub and herb layer, the presence of dead wood, saproxylic beetles, fungi and epiphytic mosses and lichens.

The mixed deciduous **Forest of Aelmoeseneie** in **Gontrode** (**LTER_EU_BE_03**) is one of the few remaining 'old' forest fragments which means it has been permanently forested since before 1775. Since 1969 this 28.5 ha forest was put at the disposal of the Department of Forest and Water Management of the University of Ghent where it serves an important educational and scientific role. Most research activities are concentrated in a marked scientific zone of 1.83 ha. Besides the Level II plot, the scientific zone contains a Level I plot, and a 35 m high meteorological tower since 1993. Furthermore, several short-term projects and MSc theses, of both ForNaLab (www.ugent.be/bw/dfwm/en/research/fornalab) and the Laboratory of Plant Ecology (www.plantecology.ugent.be), have been conducted in the forest. An overview of the study locations in the entire forest and a list of the scientific publications of studies in the Aelmoeseneie forest can be found in Vanhellemont and Verheyen (2011) (in Dutch, but with extended abstracts for each publication in English, see also www.aelmoeseneiebos.ugent.be).

The **Forest of Ravels,** largely planted with Corsican pine (*Pinus nigra ssp. laricio var. Corsicana Loud*.), hosts another ICP Forests level II intensive forest monitoring plot (**LTER_EU_BE_04**). Other long-term ecological research in the Forest of Ravels besides the study of the effects of air pollution, are the long-term records of roe deer counts coordinated by INBO in order to monitor the local roe deer population.

The mixed beech-oak woodland of the **Forest of Wijnendale** (**LTER_EU_BE_05**) comprise a strict forest reserve with a surface area of 90 ha and a ICP Forests Level II monitoring plot. The area has been covered by forest during the past centuries, but there are strong indications that it has been exploited in the Middle ages (peat extraction, fishing ponds) and was converted to arable land for a while early in the 19th century. The forest reserve officially was installed in 1996 and monitoring started in 2002. It includes an inventory of the trees, shrubs, herbs and mycoflora in 124 grid-based plots and in a 0.98 ha core area and aims at improving our understanding in the natural dynamics of unmanaged forest in Flanders. These insights will support a type of forest management that is more nature-oriented than traditional forest management.

The '**Scheldt Estuary and its alluvial plains'** (**LTER_EU_BE_06**) is situated on the border of Belgium and the Netherlands. The combination of an uninterrupted gradient in salinity from marine to a freshwater ecosystem and the far reaching influence of tides creates a patchwork of different habitats. The estuary is almost unique in Europe. Besides the ecological importance of the estuary, the socio-economic component is also of great importance. The port of Antwerp, one of the biggest in Europe, is situated 80 km upstream and is vital for Flanders economic welfare. The combination of the unique ecology and socio-economic importance of the site makes it a relevant site to conduct long term research. A lot of long term research and monitoring has already been conducted on this site, resulting in time series of up to 20 years.

The heathland reserve **'De Zoom-Kalmthoutse heide'** (**LTER_EU_BE_08**) is a complex of different habitats including dry and wet heathlands, pioneer vegetation of shifting dunes, moorland pools, species rich grasslands, deciduous woodland and pine plantations, including the strict forest reserve of the Withoefse heide with long-term ecological monitoring records since 1975. It is a intensively visited heathland reserve with a well established management and has known a series of wildfires offering research opportunities related to nature conservation and restoration, succession, fire control management etc.

The ‘**Westhoek Coastal Dunes’** (**LTER_EU_BE_09**) covers a complete gradient from beach to coastal woodland. The land is characterised by low density grazing. The vegetation succession has been monitored for over 20 years.

The ‘**Belgian Coastal Waters and Sand Bank System’** or Belgian Part of the North Sea (BPNS, **LTER_EU_BE_10**) covers the most south-western part of the North Sea and is bordered by the English Channel to the south-west and by the central part of the North Sea to the north-east. The BPNS is mainly influenced by water from the ‘channel’ and from freshwater inputs from the Yzer and Scheldt. It is dominated by sandbank systems, and together with the complex hydrodynamics and the high diversity of sediment types this makes the site unique in the North Sea not only from a geological but also from a ecological point of view.
Biotic and abiotic data is generated as part of a marine observatory that includes fixed and mobile platforms and monthly sampling campaigns covering the entire area. All stations are characterized by a shallow depth (max 30 m) and possess a wide set of biotic and abiotic features. A wide range of socio economic and human activities information is being gathered and updated on a regular basis in the framework of various related initiatives.

The site of ‘**National Park Hoge Kempen’** (NPHK, **LTER_EU_BE_11**) comprises a 5700 ha area in Eastern Belgium, dominated by wet and dry heathland, deciduous and coniferous forests, including peat bog and fens. The NPHK is located in an formal mining and urbanised area. Several research groups from universities and institutes are monitoring and measuring abiotic and biotic parameters throughout the different ecosystems. Research on ecosystem services are also playing a major role, including tourism and mobility.

The ‘**Valley of the Zwarte Beek’** (**LTER_EU_BE_12**) comprises a 10 km stretch of a stream valley managed as a nature reserve some 17 kilometer North of the city of Hasselt. Since 1995, the restoration projects are carried out aiming at restoring the fen and carr ecosystems. This is the best preserved example of an upper course of a non alluvial river valley in the northern part of Belgium. Hydrology (dynamics and chemistry) is monitored in detail as well as the vegetation in order to use the data for understanding the ecosystem functioning, and to use these data as a reference set for nature restoration projects elsewhere.

FORBIO is a large-scale forest biodiversity experiment established in Belgium between 2009 and 2012. The acronym stands for assessment of the effects of tree species diversity on FORest BIOdiversity and ecosystem functioning. At three sites with contrasting site conditions, plots were planted with one up to four tree species. Various aspects of ecosystem functioning are compared between plots that differ in tree species richness but have developed under the same abiotic conditions. The three sites form part of LTER-Belgium and are located in **Zedelgem** (**LTER_EU_BE_13**), **Hechtel-Eksel (LTER_EU_BE_14)** and **Gedinne (Gribelle, Gouverneurs) (LTER_EU_BE_15).**

The site of **Vielsalm** (**LTER_EU_BE_16**) is a mixed mature forest composed mainly of Fagus sylvatica and Pseudotsuga menziesii. Fluxes of CO_2 and water vapour are measured above the forest by an eddy-covariance system installed on a 52 meters high tower. Research activities are carried out by the University of Liège (GxABT) and Louvain-la-Neuve (UCL). The site has been equipped to follow ICOS requirements for level 2 sites in order to measure CO_2 and water vapour fluxes, meteorology, soil properties and vegetation (biomass, leaf area, …).

The **Waroneu site** (**LTER_EU_BE_17**) is a 83 ha catchment with 50% conifers (Picea abies), 43% deciduous trees (Fagus sylvatica, Quercus robur, Betula pendula) and 14% open space. **La Robinette (LTER_EU_BE_27)** is a 81 ha catchment with 8% mature and 41% young conifers (Picea abies), 7% deciduous trees (Fagus sylvatica, Quercus robur, Betula pendula, Alnus glutinosa, Sorbus aucuparia, Salix caprea) and 44% open space. On both sites biogeochemistry (nutrients and organic carbon in throughfall, rainfall, soil solution and outlet) has been studied since 1991 as a reference catchment within the frame of a liming experiment (Waroneu catchment) and critical loads calculations. Since 2013, biogeochemistry and soil microbial parameters (microbial biomass, N mineralization, basal respiration) are studied in 6 intensive plots, reflecting major combinations of vegetation and upper soil characteristics within the catchment.
The catchment of La Robinette, initially coverd by Picea abies, was subjected to windthrow and clearcut (1996), followed by afforestation with deciduous species in 1998. Four 2 ha plots were planted with deciduous species in alternate rows. Alder, rowan, birch and oak were also planted within the catchment. Biogeochemical measurements have been complemented with experiments on litterfall, litter decomposition, soil respiration and N cycle processes. La Robinette is an ICOS Belgium site.

The site of ‘**Baileux - La Sormone’** (**LTER_EU_BE_18**) comprises 4 plots installed in an oak and beech forest of 60 ha: 2 plots are in pure stands dominated either by oak (1.22 ha) or by beech (0.88 ha) and the two other plots are in mixed stands of contrasted densities (1.05 + 1.75 ha). All the stands are close to each other and are in very similar ecological conditions. On this experimental site, several studies were conducted by the Catholic University of Louvain to understand how tree species mixtures affect the ecological processes regulating the main carbon, water and nutrient fluxes. In addition, monitoring activities are carried out regularly.

The sites of **Willerzie, Dochamps, Mellier, Baelen, Tellin, Ruette, Chimay and Louvain-la-Neuve (LTER_EU_BE sites number 19 till 26**) are all ICP Forests Level II intensive monitoring plots consisting of a core fence area of 0.5 ha surrounded by a 20 m buffer area. Managment, data collection and reserch activities carried on by Catholic University of Louvain (UCL).

Bosland (LTER_EU_BE_28), established in 2006, consists of 3 municipalities Lommel, Overpelt and Hechtel-Eksel with a total area of 21982 ha. From this area, 9500 ha is nature and forest which consists largely of coniferous stands on sandy soil intermixed with remnants of heathland and land dunes. Bosland is not a research site on itself but it is a cooperation between the three communities and the Governmental Agency for Nature and Forest to come to an integrated forest and nature policy and management. Since years Bosland has a good cooperation with universities and research institutes and evolved into an open-air field laboratory. It has the aspirations to evolve into a long-term socio-ecological research platform. The FORBIO Hechtel-Eksel site and one permanent observation plot of ICP Forests are examples of two long-term ecosystem research sites located within Bosland.

The site of **Doode Bemde** (**LTER_EU_BE_29**) comprises a 4 km stretch of a complete alluvial floodplain managed as a private nature reserve some 10 kilometer upstream of the city of Leuven. Since 1990, human interference in the river channel has stopped resulting in a spontaneous meander evolution and roughening of the river channel. This has induced frequent (e.g. yearly) inundations, thus avoiding flood damage in the city of Leuven downstream and this without creating the usual storm basins. Monitoring of the meander movements, the ground- and surface water dynamics and chemistry, the vegetation evolution is carried out by INBO and VMM.

Rode Forest (LTER_EU_BE_30) consists of a strict forest reserve (since 1989) which has been permanently wooded with deciduous trees since more than 230 years. It consists of a valley part, a slope part and a plateau part. The slope habitats are influenced by an aquifer that feeds the slope sources. Hydrochemically, the water can be characterized as acid and nutrient poor. The slope displays an acid tolerant vegetation with Sphagnum as well as a more neutrophilic Querceto-Carpinetum.

Meerdaal Forest (LTER_EU_BE_31) is a mixed beech and oak woodland, combined with valley grasslands and woodlands. It is located in the community of Sint-Joris-Weert, south of Leuven, on the loess plateau of Brabant. This LTER-site contains several strict forest reserves in which stand dynamics and vegetation changes have been monitored since 2003. Additional standardised sampling of Saproxylic beetles, mosses and fungi were performed. In the managed parts of this state forest, many other scientific experiments have been performed, mostly by the University of Leuven. Furthermore it contains an ICP Forests Level II monitoring plot.

The three LTER-sites of Doode Bemde, Rode Forest and Meerdaal Forest have common borders and possess potential to develop into a LTSER-platform.

Lake Kraenepoel (LTER_EU_BE_32) is a shallow lake (22 ha), divided in two basins . The lake was used for fish farming until World War II and was drawn down about every 5 years to harvest fish. Despite its dense historical carp population, it had clear water and a rich Littorelletea vegetation. During the course of the 20th century, the lake became eutrophic and the Littorelletea vegetation degraded. The northern basin, which was still drawn down about every decade after 1957, retained its clear water and had a dense submerged macrophyte vegetation. The southern basin, which was never drawn down after 1957 and which received direct surface water inputs, had become a turbid shallow lake with phytoplankton blooms in summer. In 2000, efforts were taken to restore the lake: the entire lake was drawn down, the fish community was biomanipulated, nutrient-rich surface water inputs were diverted from the southern basin and sediments were removed (only in the northern basin). Fish biomanipulation and sediment removal were successful in the northern basin, as nutrient levels declined and the Littorelletea vegetation recovered. In the southern basin, sediment analyses indicated that drawdown resulted in sediments with a lower water and organic matter content and water column turbidity decreased after the drawdown.

The **Lonzée ecosystem station (LTER_EU_BE_33),** installed in 2004 thanks to funds from the European Community and Communauté française de Belgique (ARC project), was one of the first European carbon flux sites devoted to production crops. This set-up allowed to follow net CO_2 fluxes exchanged between a four year rotation crop and contains a 3 m high mast. It is part of ICOS Belgium. Measured parameters are intensive biomass monitoring, soil respiration, NDVI and PRI, nitrogen, volatile organic compounds fluxes, N_2O fluxes.

Concerning the representation of the Belgian ecosystems in the LTER-Belgium research network, there is a very strong representation of the forest ecosystems (72% of the sites/platforms, Table 2).

Table 2 Representation of the major ecosystems in the LTER-Belgium network

Dominant ecosystem	**Number of sites/platforms**
Temperate broadleaf and mixed forests	15
Temperate coniferous forests	8
Temperate grasslands, savannas, shrublands	3
Estuary	1
Temperate shelfs and seas	1
Heathland, scrub and tundra	1
Coastal dunes	1
Small lakes	1
Agricultural crop system	1
Total	**32**

2 Intensive forest monitoring (Level II) in Flanders

Atmospheric deposition of inorganic nitrogen (N) and sulphate caused N saturation and acidification of temperate forest soils and surface waters in large parts of Europe and North America since the 1950's. Along with the growing awareness of environmental problems, national policies and international cooperation to abate acidifying emissions were implemented since the late 1970's, like the Convention on Long-range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE) (www.unece.org). This led to the installation of large-scale forest monitoring networks like ICP Forests (www.icp-forests.org), which had the initial target to follow up forest condition (Level I) and to study the effects of air pollution on forest condition with specific attention for ecosystem processes (Level II). Later on the focus was widened to other factors that could influence forest condition, including climate change, site conditions (e.g. history and soil type) and management.

2.1 Level II core plots

In Flanders, 72 ICP Forests Level I plots and 12 Level II plots (circular plots, with an area of 0.25 ha each) were installed in 1987–1991 (Figure 2). Since 2002 the monitoring activities are carried out by the Research Institute for Nature and Forest (INBO) (www.inbo.be/nl/onderzoeksgroepen/milieu-klimaat). Currently, five of these Level II plots are followed up as intensive monitoring sites (Level II core plots), while a more limited monitoring program is conducted in six plots (Level II additional plots) and one plot was abandoned in 2002 because of groundwater contamination. Two of the Level II core plots are equipped with a measuring tower for the survey of air components at different heights. All Level II plots are located in forest stands which have a regular forest management (mainly aimed at wood production), conducted by the Flemish Agency of Nature and Forests (ANB) (www.natuurenbos.be).

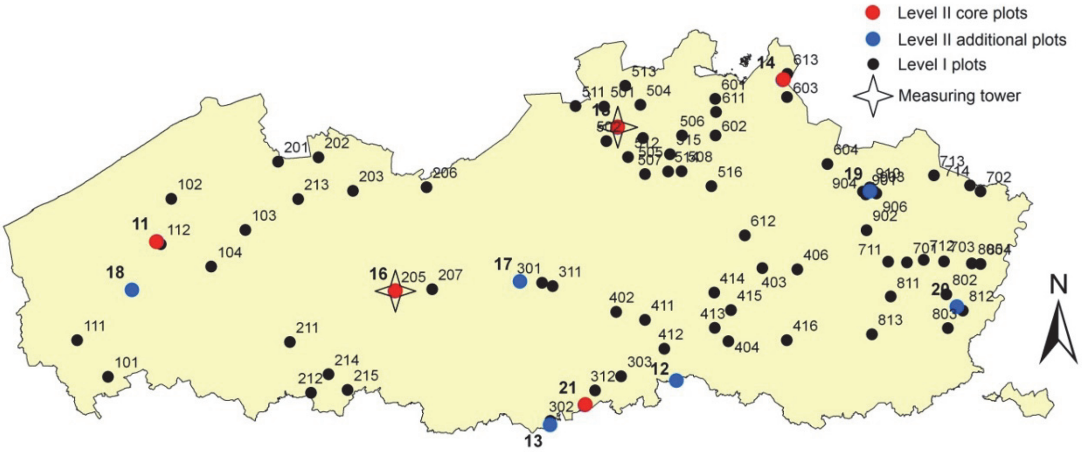

Figure 2 The network of Level I and Level II plots in Flanders.

In this chapter we present an overview of the monitoring activities in the five Level II core plots in Flanders, including a number of results. Site and soil characteristics of the five Level II core plots are given in Table 3 and Table 4.

Table 3 Characteristics of the five Level II core plots. Mean annual temperature (MAT) and precipitation (MAP) are long-term averages for the nearest meteorological station (1981–2010, Royal Meteorological Institute of Belgium, www.meteo.be). Basal area was calculated from a full survey (DBH ≥ 5 cm) in 2009–2010. Humus types were defined in 2007 (Zanella et al., 2011).

Plot nr.	name	Coordinates N	E	Elevation m	MAT °C	MAP mm	Tree species	Planting year	Former use	Basal area m² ha^{-1}	Humus type	Rooting depth (cm)	Groundwater range (m)
Coniferous forests													
14	Ravels	51°24'07''	05°03'15''	35	10.4	887	*Pinus nigra* ssp. *laricio* var. *Corsicana* Loud.	1930	heath	44.9	mor	185	1.5–2.5
15	Brasschaat	51°18'28''	04°31'11''	14	10.8	882	*Pinus sylvestris* L.	1929	heath	29.2	mor	160	1.2–2.3
Deciduous forests													
11	Wijnendale	51°04'11''	03°02'14''	31	11.0	867	*Fagus sylvatica* L.	1935	arable	36.5	mor	170	0.9–2.3
16	Gontrode	50°58'31''	03°48'15''	26	10.6	786	*Quercus robur* L., *Fagus sylvatica* L..	1918	old growth	31.9	moder	180	1.5–1.8
21	Hoeilaart	50°44'45''	04°24'47''	129	10.7	854	*Fagus sylvatica* L.	1909	old growth	28.9	moder	195	>30

Table 4 Soil characteristics of the five Level II core plots: soil type according to IUSS Working Group WRB 2006 (2007), sampling depths, morphogenetic horizons, C:N ratio, pH-CaCl2, cation exchange capacity (CEC) and base saturation (BS) for the forest floor layers (OF, OH or OFH) and five fixed depth layers of the mineral soil. Soil texture data are given for the mineral soil layers (clay, silt and sand fractions in %). Soil samples were sampled and analysed following the ICP Forests manual (ICP Forests, 2010).

Plot	Soil type (WRB 2006, update 2007)	Depth cm	Morphogenetic Horizon	C:N	pH $CaCl_2$	CEC $cmol_c\ kg^{-1}$	BS %	Clay 0–2 µm	Silt 2–63 µm	Sand 63-2000 µm
RAV	Endogleyic Folic Brunic Albic **Arenosol** (Dystric)	–6.6 to –0.8	OF	33	2.5	23	36			
		–0.8–0	OH	35	2.3	26	16			
		0–5	Ap/E	27	2.9	4.6	11	2.3	10.2	87.5
		5–10	Ap/E	27	3.0	3.8	7.6	0.9	12.6	86.5
		10–20	Ap/E	23	3.1	3.6	7.4	0.7	11.9	87.4
		20–40	Bhs	21	3.4	3.3	8.2	3.0	12.0	85.0
		40–80	B, Bg1	-	4.1	1.7	15	1.4	12.3	86.3
BRA	Endogleyic Brunic Albic Hypoluvic **Arenosol** (Dystric)	–5.2–0	OFH	30	2.7	25	42			
		0–5	Ap1	18	3.1	2.2	18	2.0	7.0	91.0
		5–10	Ap1	18	3.2	1.8	15	1.9	4.7	93.4
		10–20	Ap1	15	3.3	1.7	16	1.8	5.9	92.3
		20–40	Ap1, Ap2	14	3.4	1.6	17	1.0	6.1	92.8
		40–80	E, Bg1, Bg2	-	3.6	1.5	18	1.6	5.3	93.1
WIJ	Endogleyic Folic **Umbrisol** (Brunic, Humic, Alumic, Hyperdystric, Arenic)	–8.0 to –2.1	OF	25	2.7	31	42			
		–2.1–0	OH	22	2.7	25	23			
		0–5	A1	21	2.5	7.3	32	–	–	–
		5–10	A2	19	2.7	4.2	14	3.3	24.7	72.0
		10–20	A2	16	3.0	3.5	11	3.8	23.8	72.5
		20–40	A3	18	3.3	3.1	10	3.6	21.5	74.9
		40–80	Bhg, Cgc	10	3.6	3.0	11	5.9	21.9	72.2
GON	Luvic **Planosol** (Albic, Ruptic, Dystric, Siltic, Clayic)	–6.2–0	OFH	25	3.6	–	–			
		0–5	A	20	2.9	17	23	–	–	–
		5–10	B	17	2.9	15	20	9.5	50.6	39.9
		10–20	B, 2B	17	3.0	12	15	11.0	48.2	40.8
		20–40	2B, 2Bg	12	3.3	14	21	24.5	46.0	29.5
		40–80	2Bg, 3Bg	7.8	3.5	23	61	47.5	36.6	15.9
HOE	Albic Cutanic **Alisol** (Fragic, Abruptic, Alumic, Hyperdystric, Siltic)	–3.0–0	OFH	23	3.1	24	81			
		0–5	A	17	3.3	6.3	16	10.6	85.9	3.6
		5–10	Bh	17	3.5	4.3	13	5.3	90.7	4.0
		10–20	E	14	3.8	3.8	11	14.4	81.8	3.8
		20–40	Bt	10	3.8	4.6	8.9	13.5	81.3	5.2
		40–80	Btx1	5.4	3.8	5.2	16	19.1	76.9	4.0

2.1.1 Wijnendale (nr. 11)

Level II core plot nr. 11 is located in the Wijnendale forest in the community of Ichtegem, in the western part of Sandy Flanders. It is an important component of the LTER-site Forest of Wijnendale (LTER-EU-BE-05).
The LTER-site further contains a large strict forest reserve (90 ha), where dynamics of forest structure and vegetation are monitored since 2002, and a comparable, managed state forest area, where no specific monitoring activities are organised up to now. In the strict reserve, also standardized samplings of mosses, lichens, fungi and saproxylic beetles have been performed.

The surrounding area is farmland, and consists mainly of arable land. The soil is a sandy loam soil (Umbrisol) with presence of clay below 90 cm depth, a shallow groundwater table, moderately low base saturation in the mineral soil and slightly higher base saturation in the topsoil.
The forest stand in which the core plot is located is a homogeneous European beech stand (*Fagus sylvatica* L.), which was planted in 1935. Since the start of monitoring, the stand structure has been characterized by the absence of a moss layer, herb layer and understory, which could be explained by the shady conditions and the thick organic layer (Figure 3).

Figure 3 Level II core plot Wijnendale (nr. 11).

2.1.2 Ravels (nr. 14)

Level II core plot nr. 14 is located in the forest 'Gewestbos Ravels-Noord' (820 ha), in the community of Ravels, in the northern Campine ecoregion of Flanders. The core plot has a size of 0.5 ha, and constitutes the LTER-site LTER_EU_BE_04 'Ravels forest'.

The surrounding area is agricultural, with a high concentration of livestock breeding farms. The soil is a well-drained sandy soil (Arenosol) with a C:N ratio of 33–35 in the organic layer (mor humus). The forest stand in which the core plot is located is a homogeneous Corsican pine stand (*Pinus nig*ra ssp. *laricio* var. *Corsicana* Loud.), which was planted in 1930 on former heathland (Figure 4). The herb layer is dominated by Broad Buckler Fern (*Dryopteris dilatata* Hoffm.), Bilberry (*Vaccinium myrtillus* L.) and purple Moor Grass (*Molinia caerulea* (L.) Moench). A sparse understory of silver birch (*Betula pendula* L.) and rowan (*Sorbus aucuparia* L.) is developing since several trees were felled by a storm in January 2007.

Figure 4 Level II core plot Ravels (nr. 14).

2.1.3 Brasschaat (nr. 15)

Level II core plot nr. 15 is located in the forest 'De Inslag' (150 ha), in the community of Brasschaat, in the northern Campine ecoregion of Flanders. The core plot has a size of 0.5 ha, and is located within the fenced scientific zone of 2 ha which constitutes the LTER-site LTER_EU_BE_001 'Brasschaat De Inslag'.
The forest is located in an urban area at 10 km east from the port of Antwerp, which emits more than half of the SO_2 emissions in Flanders. The soil is a sandy soil (Arenosol) with a C:N ratio of 30 in the organic layer (mor humus). The infiltration of water is locally slowed down by clay lenses at 50–125 cm depth. The forest stand in which the core plot is located is a homogeneous Scots pine stand (*Pinus sylvestris* L.), which was planted in 1929 on former heathland (Figure 5). The herb layer is dominated by *Molinia caerulea* (L.) Moench and several ferns. The stand structure is further characterized by a diverse moss layer and ingrowth of several tree and shrub species (*Betula pendula* L., *Frangula alnus* Mill., *Sorbus aucuparia* L., …). Besides the Level II monitoring plot, the site contains a 40 m high measuring tower, where meteorological variables and the concentrations of air pollutants are monitored above and below the canopy since 1995. The scientific area and the surrounding forest also function as a Belgian ICOS measuring site (www.icos-belgium.be), which is coordinated by the Research Centre of Excellence PLECO (Plant and Vegetation Ecology) of the University of Antwerp (www.uantwerpen.be/en/rg/pleco).

Figure 5 Level II core plot Brasschaat (nr. 15) with a view of the measuring tower.

2.1.4 Gontrode (nr. 16)

Level II core plot nr. 16 is located in the Aelmoeseneie forest (28.5 ha), which is the experimental forest of the University of Ghent. This experimental forest forms the LTER-site 'LTER_EU_BE_03 : Gontrode – Aelmoeseneie Forest'. The forest is located in the community of Gontrode, in the Dender-Klein Brabant ecoregion. At the core plot, the soil consists of a silt loam to loam soil (Planosol), overlaying a mosaic of tertiary clayey and sandy deposits with high base saturation starting at 50 cm depth. The forest stand in which the plot is located, is a mixed stand, dominated by common (pedunculate) oak (*Quercus robur* L.) and European beech (*Fagus sylvatica* L.), and further containing ash (Fraxinus excelsior), larch (Larix spp.) and maple (Acer pseudoplatanus). The main tree layer was planted shortly after the first World War in an ancient woodland site (Figure 6). The herb layer is moderately developed and consists of bramble (*Rubus fruticosus* L.) and a limited number of typical forest plant species (e.g. *Polygonatum multiflorum* (L.) All.). The understory is rather dense and consists mainly of common hazel (*Corylus avellana* L.), sycamore maple (*Acer pseudoplatanus* L.) and rowan (*Sorbus aucuparia* L.). The Level II plot is located in a fenced scientific area (1.83 ha) in the forest, which contains a 35 m high measuring tower, where meteorological variables and tree phenology and physiology are monitored. The scientific area is operated by the Forest & Nature Lab (ForNaLab) (www.ugent.be/bw/dfwm/en/research/fornalab) and the measuring tower by the Laboratory of Plant Ecology (www.plantecology.ugent.be) of the University of Ghent.

Figure 6 Level II core plot Gontrode (nr. 16) with a view of the measuring tower.

2.1.5 Hoeilaart (nr. 21)

Level II core plot nr. 21 is located in the Sonian forest in the community of Hoeilaart, in the central hills of Flanders.. This core plot has a size of 0.5 ha, and constitutes an important component of the LTER-site 'LTER_EU_BE_02 'Sonian Forest', that covers the whole forest complex (4400 ha). The forest is surrounded by residential areas near the southeastern border of the city of Brussels, and is crossed by several highways. The soil is a loamy loess soil, with moderately low base saturation and deep groundwater table (>30 m).

The forest stand in which the core area is located is a homogeneous stand of European beech (*Fagus sylvatica* L.), which was planted in 1909 on an ancient woodland site (Figure 7). The herb layer is well developed and hosts several ancient forest plant species (*Hyacinthoides non-scripta* (L.) Rothm., *Hypericum pulchrum* L., *Lamium galeobdolon* (L.) L. subsp. *montanum* (Pers.) Hayek, *Luzula pilosa* (L.) Willd., *Maianthemum bifolium* (L.) F.W.Schmidt, *Moehringia trinerva* (L.) Clairv., *Oxalis acetosella* L., *Polygonatum multiflorum* (L.) All.). Since 2006 an understory of beech and sycamore maple (*Acer pseudoplatanus* L.) started to develop in the plot.

Figure 7 Level II core plot Hoeilaart (nr. 21).

2.2 Additional Level II plots

Besides the five Level II core plots, there are six additional Level II plots in Flanders, where a more limited monitoring program is conducted (Table 5). Three of these plots are situated within an LTER-site and/or platform.

Table 5 Characteristics of the six additional Level II plots in Flanders.

Plot		Coordinates		Elevation	Tree Species	Planting	Part of LTER-site or LTSER-platform
nr.	name	N	E	m		year	
Coniferous forests							
19	Pijnven	51°10'29''	05°19'58''	52	*Pinus nigra* ssp. *laricio* var. *Corsicana* Loud.	1930	LTER_EU_BE_28 Bosland
20	Heiwijk	50°56'19''	05°36'24''	103	*Pinus sylvestris* L.	1943	LTER_EU_BE_11 NPHK
Deciduous forests							
12	Meerdaal	50°47'42''	04°42'20''	60	Mixed (*Quercus robur* L.)	?	LTER_EU_BE_31 Meerdaal Forest
13	Halle	50°42'22''	04°18'07''	119	*Fagus sylvatica* L.	1944	-
17	Buggenhout	50°59'46''	04°12'19''	25	*Fagus sylvatica* L.	1842–1892	-
18	Houthulst	50°58'15''	02°57'35''	26	*Quercus robur* L.	1922	-

Level II plot nr. 12 is located in the Meerdaal forest, in the community of Sint-Joris-Weert, south of Leuven, on the loess plateau of Brabant and is part of the LTER-site Meerdaal forest (LTER_EU_BE_31). The forest stand in which the core-area is located is a stand of common oak (*Quercus robur* L.) mixed with *Carpinus betulus* L., *Acer pseudoplatanus* L., *Ulmus minor* Mill. and *Alnus incana* (L.) Moench. The understory consists of *Corylus avellana* L. and *Prunus serotina*. The whole forest is an ancient woodland site. The herb layer hosts several ancient forest plant species, including *Carex sylvatica* Hudson, *Convallaria majalis* L., *Lamium galeobdolon* (L.) L. subsp. *montanum* (Pers.) Hayek, *Luzula pilosa* (L.) Willd., *Maianthemum bifolium* (L.) F.W.Schmidt, *Milium effusum* L., *Oxalis acetosella* L. and *Stellaria holostea* L. (Figure 8).

Figure 8 Level II plot Meerdaal (nr. 12).

Level II plot nr. 13 is located in the forest of Hallerbos, in the community of Halle, southwest of Brussels, on the loess plateau of Brabant. This site is not located in an LTER-site.

The forest stand in which it is located is a homogeneous stand of European beech (*Fagus sylvatica* L.), which was planted in 1944 in an ancient woodland site. The herb layer is dominated by Common Bluebell (*Hyacinthoides non-scripta* (L.) Rothm., showing a characteristic purple-blue bluebell carpet in spring (Figure 9).

Figure 9 Level II plot Halle (nr. 13).

Level II plot nr. 17 is located in the Buggenhout forest, in the community of Buggenhout, in the Dender-Klein Brabant ecoregion. It is not located in an LTER-site. The forest stand consists of an open homogeneous stand of European beech (*Fagus sylvatica* L.), which was planted in 1842–1892. The understory is lacking. The herb layer is dominated by bracken (*Pteridium aquilinum* (L.) Kuhn) (Figure 10).

Figure 10 Level II plot Buggenhout (nr. 17).

Level II plot nr. 18 is located in the Houthulst forest, in the community of Houthulst, in the western part of Flanders. This plot is not located in an LTER-site.

The forest stand consists of common oak (*Quercus robur* L.) which was planted in 1922, with ingrowth of *Quercus rubra* L., *Betula pubescens* Ehrh. and *Castanea sativa* Mill. in the tree layer and understory. The herb layer is dominated by bramble (*Rubus fruticosus* L.) and bracken (*Pteridium aquilinum* (L.) Kuhn) (Figure 11). This site is an ancient woodland site, but was completely devastated during the first WW.

Figure 11 Level II plot Houthulst (nr. 18).

Level II plot nr. 19 is located in the Pijnven forest, in the community of Hechtel, in the Campine ecoregion of Flanders. The plot is located in one of the Belgian LTSER-platforms (LTER_EU_BE_28). Within the platform various types of research and monitoring, also involving volunteer networks, are performed.

The forest stand of the core area is a homogeneous Corsican pine stand (*Pinus nigra* ssp. *laricio* var. *Corsicana* Loud.), which was planted in 1930. The understory consists of Corsican pine seedlings, *Larix decidua* Mill. and *Prunus serotina*. The herb layer is dominated by *Deschampsia flexuosa* (L.) Trin. and *Molinia caerulea* (L.) Moench (Figure 12).

Figure 12 Level II plot Pijnven (nr. 19).

Level II plot nr. 20 is located in the Heiwijk forest, in the community of Maasmechelen, in the Campine ecoregion of Flanders. It is part of the LTSER-platform ‘National Park Hoge Kempen’ (LTER_EU_BE_11). This platform covers over 5700 ha and consists of both forest and heathland areas. A wide range of research activities and surveys are being performed here.

The forest stand in which the core area is located is an even-aged Scots pine stand (*Pinus sylvestris* L.), which was planted in 1943. The stand structure is characterized by a diverse moss layer and ingrowth of several tree and shrub species (*Frangula alnus* Mill, *Quercus robur* L., *Sorbus aucuparia* L., …). The herb layer is quite varied, with *Vaccinium myrtillus* L., *Deschampsia flexuosa* (L.) Trin., *Dryopteris dilatata* Hoffm. and *Molinia caerulea* (L.) Moench as the main species.

Figure 13 Level II plot Heiwijk (nr. 20).

2.3 Monitoring program

The monitoring program in the Level II core plots consists of several surveys, which are carried out on a regular basis. Surveys include atmospheric deposition, soil and soil water, ground vegetation, tree growth, crown condition, foliar concentrations, concentrations of air pollutants, meteorological variables, LAI and phenology. In the additional plots a more limited monitoring program is conducted. Table 6 presents an overview of the different surveys in the Level II plots and the normal frequency of execution.

Table 6 Overview of the different surveys, current frequency of execution and the number of Level II core plots and additional plots where each survey is carried out.

Survey	Frequency	Core plots	Additional plots	Start[a]
Soil chemistry	Every 10 years	5	6	1992
Ground vegetation	Every 5 years	5	6	1988
Forest inventory	Every 5 years	5	6	1988
Growth				
- Girth bands	Before and after growing season	5	6	2007
- Point dendrometers	Continuously	1	-	2014
Crown condition	Every year	5	6[b]	1988
Atmospheric deposition				
- Open field	Continuously (halfmonthly sampling)	5	-	1993
- Throughfall	Continuously (halfmonthly sampling)	5	-	1992
- Stemflow	Continuously (halfmonthly sampling)	3	-	1994
Soil solution chemistry				
- Organic layer	Continuously (halfmonthly sampling)	5	-	1993
- Mineral soil	Continuously (halfmonthly sampling)	5	-	1992
Soil water content	Every 6 hours	5	-	1996
Ground water level	Halfmonthly	4	-	1999
Litterfall	Continuously (halfmonthly sampling)	5	-	1999
Foliar concentrations	Every 2 years	5	6[c]	1988
Meteorology	Continuously	3	-	2011
LAI	Every year (summer and winter)	3	-	2009
Phenology				
- Observers	Every week (spring and autumn)	5	1	2002
- Camera's	Continuously	1	-	2014
Air pollutant concentrations				
- Passive samplers (O_3, NH_3)	Continuously (halfmonthly sampling)	5	-	2009
- Monitors (O_3, NH_3, SO_2, NO_x)	Continuously	1	-	1995
Sapflow	Continuously	1	-	2014
Soil temperature	Every 6 hours	5	-	1996

[a] in this year the first measurements were conducted, but not necessarily at all plots and at the current frequency
[b] until 2009
[c] until 2007

2.4 Materials and methods

2.4.1 Atmospheric deposition sampling and analysis

Atmospheric deposition is sampled and analysed according to the guidelines of the ICP Forests manual, part XIV (ICP Forests 2010). Samples of deposition are collected two times per month.

2.4.1.1 Precipitation

Precipitation is sampled with four bulk collectors, located in the open field nearby each of the Level II core plots (Figure 14). The bulk collectors consist of a polyethylene (PE) funnel (14 cm Ø), which is placed horizontally on a polyvinylchloride (PVC) pipe at 1 m height. At 10 and 90 cm height, the pipe has two openings (10 cm Ø) for ventilation. A nylon mesh (1 mm^2 mesh size) is placed in the funnel to avoid contamination by large particles. The funnel drains to a 2 L PE bottle through an opaque PVC tube. The bottle is placed in a soil pit, to keep the sample cool and shielded from sunlight.

Figure 14 Scheme of a bulk collector and view of the precipitation collectors in the open field near the Level II core plot in Ravels (nr. 14).

At every sampling event, the volume (mm) collected in each precipitation collector is measured. The four samples are bulked to one composite sample (excluding samples that are contaminated by bird droppings, if visible), using the entire collected volume. A 500 ml subsample is transported in a cooled box to the laboratory.

Upon arrival in the laboratory, the pH (Multi 340i-glass electrode, WTW) and conductivity (Multi 340i-Tetracon®325, WTW) are determined on an unfiltered subsample. Another subsample is filtered (0.45 µm), stored in darkness at 4 °C and analysed within 48 hours after sampling. The concentrations (mg L^{-1}) of cations (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, NH_4^{+}), and anions (Cl^{-}, SO_4^{2-}, NO_3^{-}, NO_2^{-}, PO_4^{3-}) are determined simultaneously using ion chromatography (Dionex ICS-3000, LOQ = 0.1 mg L^{-1}). The concentrations of Total Kjeldahl Nitrogen (TKN) (mg L^{-1}) are determined using the continuous flow method (Skalar, limit of quantification, LOQ = 0.5 mg L^{-1}). Total nitrogen concentrations are determined using a C/N analyser (Skalar, Formacs^{HT}, LOQ = 0.5 mg L^{-1}). The concentrations of DOC are determined using a TOC-analyser (Shimadzu TOC 5050A, LOQ = 1 mg L^{-1}) and since 2014 using a C/N analyser (Skalar, Formacs^{HT}, LOQ = 1 mg L^{-1}). Total alkalinity is determined (if pH > 5.0) titrimetrically with 0.01 M HCl.

2.4.1.2 *Throughfall*

Throughfall is sampled in each core plot with ten bulk collectors of the same type as the precipitation collectors in the open field. The throughfall collectors are arranged systematically, according to a northeast-southwest oriented line-cross with its centre as close as possible to the central point of the plot (Figure 15).

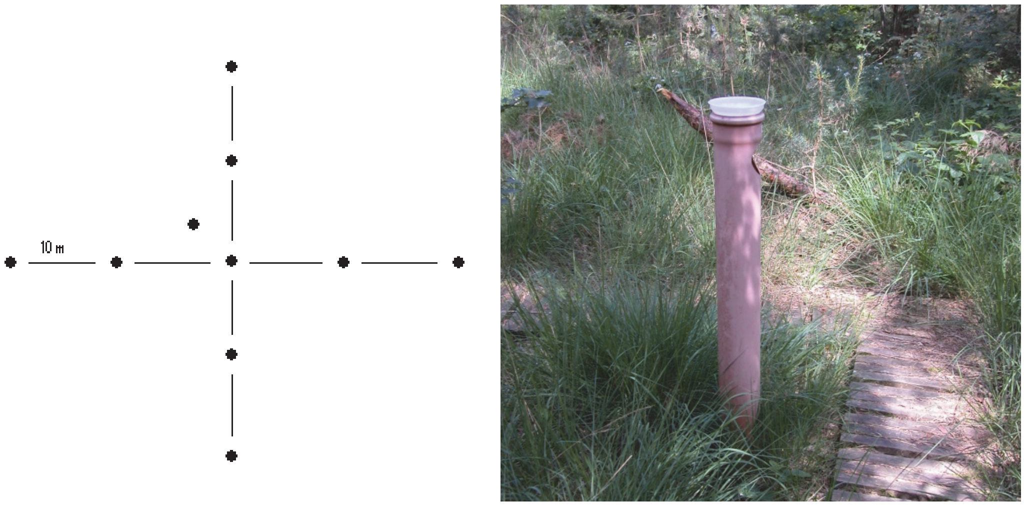

Figure 15 Scheme of the arrangement of throughfall collectors (left) and throughfall collector at the Level II core plot in Brasschaat (nr. 15).

At every sampling event, the volume (mm) collected in each throughfall collector is determined. The ten samples are bulked to one composite sample (excluding samples that are contaminated by bird droppings, if visible), using the entire collected volume. A 500 ml subsample is transported in a cooled box to the laboratory. Chemical analyses are identical to those of precipitation samples.

2.4.1.3 *Stemflow*

Stemflow sampling is conducted only for *Fagus*, since stemflow for *Pinus* and *Quercus* appeared to be negligible during a preceding testing period. In each Level II core plot in deciduous forest (n = 3) five trees of different size were selected for stemflow analysis (mean diameter, ±1 times and ±2 times the standard deviation of the initial tree population in 1994). Stemflow collectors consist of flexible PVC collars/gutters (7 cm Ø) attached horizontally to the stem at 1 m height, draining to a series of 200 L PE storage containers mounted in a cascade system (Figure 16). In each of the three plots one tree is equipped recently with a tipping bucket and data logger, in order to obtain more accurate information about stemflow (Figure 16). The volume collected by each individual tree is determined at every sampling event. Stemflow volumes, obtained from the individual trees, are upscaled to plot level using information of basal area. Subsamples are taken from all full containers, with subsample volumes weighted to tree diameters, and bulked to one sample. A 500 ml subsample is transported in a cooled box to the laboratory. Chemical analyses are identical to those of precipitation and throughfall samples.

Figure 16 Stemflow collector with containers in the Level II plot in Wijnendale (nr. 11) (left) and with tipping bucket and data logger in the Level II plot in Hoeilaart (nr. 21).

2.4.2 Soil solution sampling and analysis

Soil solution is sampled and analysed according to the guidelines of the ICP Forests manual, part XI (ICP Forests 2010). Samples of soil solution are collected two times per month.

Soil solution from the O horizon (forest floor) is sampled with four randomly located zero-tension lysimeters per plot (six in Wijnendale). The zero-tension lysimeters consist of a five cm high stainless steel box covered with a nylon mesh (1 mm^2 mesh size), installed just below the forest floor, and draining to a 2 L PE bottle in an open soil pit (Figure 17).

Soil solution from the mineral soil is sampled with ceramic cup suction lysimeters (Eijkelkamp) at three locations per plot (Figure 17). Each location is equipped with two to four lysimeters at each of three depths in the capillary zone (A, B and C horizon). The lysimeters are pressurized to 0.6 bar using a vacuum pump two days before sampling.

Soil solution samples are bulked to one composite sample per depth per plot at every sampling event, using the entire collected volume. A 500 ml subsample of each fraction is transported in a cooled box to the laboratory. Chemical analyses are almost identical to those of deposition samples, but additionally the total elemental concentrations of Al, Fe, Mn, Si (mg L^{-1}) are measured with a Liberty II plasma emission spectrometer (ICP), LOQ = 0.1 mg L^{-1}.

Figure 17 Zero-tension lysimeter (left) and tension lysimeter in the Level II plot in Ravels (nr. 14).

2.4.3 Sampling and analysis of the soil

In 1992 a first soil survey on 12 Level II plots was conducted according to the manual on sampling and analysis of soils of ICP Forests. Though at that time the methods were not yet fully harmonized. Based on 36 subsamples, composite samples were made according to genetic horizons and analyzed.

In 2003 the manual on sampling and analyses of soils of ICP Forests was revised. In order to improve comparability across sites and across Europe, it became mandatory to sample according to fixed depth layers till a depth of 80 cm. Furthermore, laboratory analytical methods were harmonized and a quality control programme was initialized. In 2004 the soil sampling was repeated on 11 Level II plots.

Ten years later, in 2014, the soil survey was repeated on these 11 Level II plots following exactly the same methodology as in 2004. The laboratory results are available now though the comparison over time yet has to be made. This will be done in the course of 2016.

2.4.4 Litterfall sampling and analysis

Litterfall is sampled and analysed according to the guidelines of the ICP Forests manual, part XIII (ICP Forests, 2010). Litterfall is sampled with ten mesh traps, each of which is installed at approximately two meters distance from a throughfall collector (Figure 18). The traps consist of a double water permeable net (mesh size 0.25 mm^2) made from chemically inert fabric with an incorporated circular PE frame (60 cm Ø) mounted horizontally on three wooden poles at 1 m height. Samples of litterfall are collected monthly from January till August and two times per month from September till December (which is the main litterfall period). At every sampling event the entire volume collected in the ten traps is bulked and transported to the laboratory in closed PE bags.

Figure 18 Scheme of the arrangement of litterfall collectors (left) and litterfall collector at the Level II core plot in Brasschaat (nr. 15).

Upon arrival in the laboratory, the samples are oven dried for three days at 40 °C and weighed to determine the dry biomass. Then each sample is split up into different fractions (leaves/needles, fruits and seeds, woody fragments, bud scales,…) and the dry weight of each subsample is determined. The weighed subsamples are ground to a homogeneous powder in a suitable mill and stored in closed black PE boxes until the annual total of material is accumulated. After all samples have been collected, all the material is thoroughly mixed for each fraction separately, and a subsample is taken for chemical analysis. Each sample is destructed by microwave digestion with aqua regia (wet ashing). The dry matter content is determined by combustion (105 °C). The content of Ca, K, Mg, Al, Fe, P and S is determined with ICP-AES (Liberty Series II). The N and C content are determined using a C/N analyser (Skalar, Formacs^{HT}).

2.4.5 Sampling and analysis of leaves and needles

Leaves and needles are sampled and analysed according to the guidelines of the ICP Forests manual, part XII (ICP Forests 2010). Fresh leaves and needles are sampled once every two years in each Level II core plot. The samples are collected by a professional tree climber, each time from the same five trees, and from the light receiving part of the canopy (Figure 19). The samples are transported to the laboratory in closed PE bags.

Figure 19 Sampling of leaves.

In the laboratory, 1000 needles or 500 leaves from each tree are selected, oven dried at 40 °C and weighed to determine the dry biomass. Each sample is then ground to a homogeneous powder in a suitable mill and a subsample is taken for chemical analysis. Each sample is destructed by microwave digestion with aqua regia (wet ashing). The dry matter content is determined by combustion (105 °C). The content of Ca, K, Mg, P, S, Al, Fe, Zn, Mn, Cd, Cu, Cr, Pb and Ni is determined with ICP-AES (Liberty Series II). The N and C content are determined using a C/N analyser (Skalar, Formacs^{HT}).

2.5 Trends and patterns

2.5.1 Atmospheric deposition

2.5.1.1 Precipitation

The annual precipitation amount in the open field showed a considerable inter-annual variation at the five Level II core plots, but no significant trend could be detected between 1994 and 2014 (Figure 20). Particularly wet years were 1998–2002 and 2011, while 1996, 1997 and 2003 were drier than average.

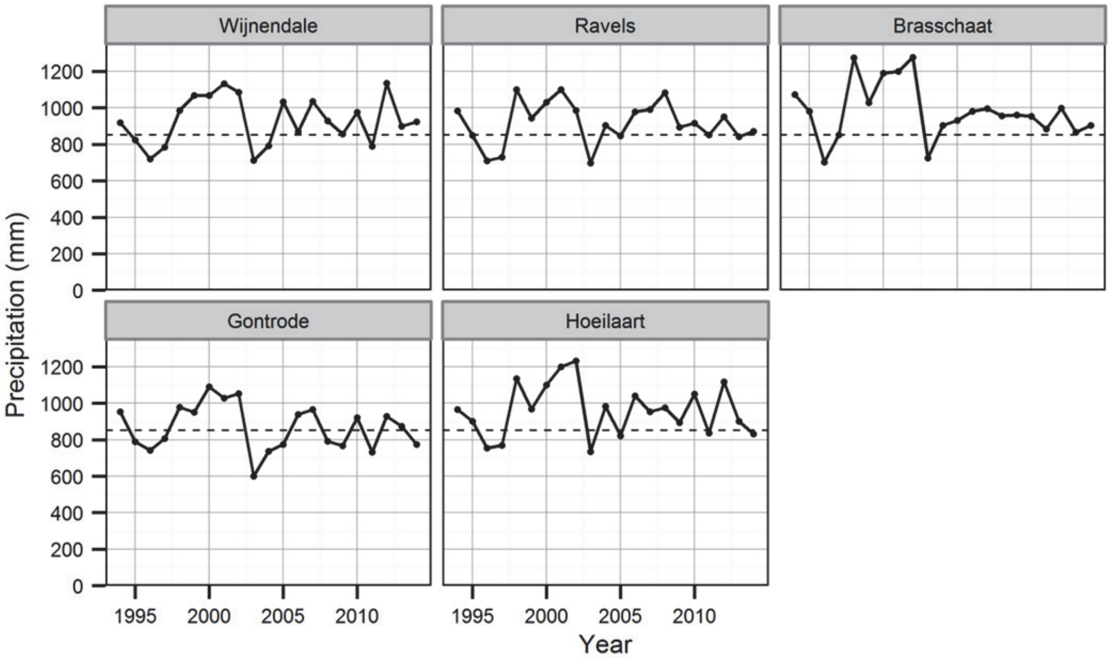

Figure 20 Annual precipitation amounts (mm) (1994–2014). Dashed line: 30-year average for Belgium (1981–2010, www.meteo.be).

The precipitation amounts in the open field are not equally distributed over the year (Figure 21). On average, August and December are the wettest months, while April is the driest month.

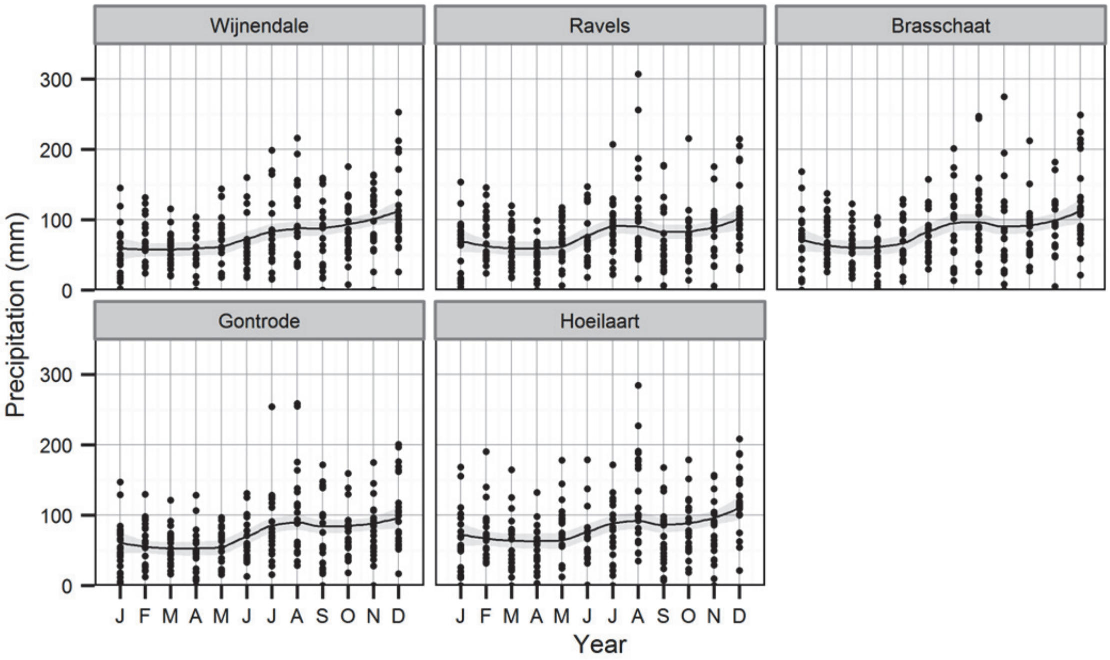

Figure 21 Monthly precipitation (mm) (1994–2014).

The pH of precipitation in the open field showed no clear trend over the monitoring period. But if we look more in detail, the pH of precipitation generally decreased during the first years (1994–2004) and then started to increase again (Figure 22).

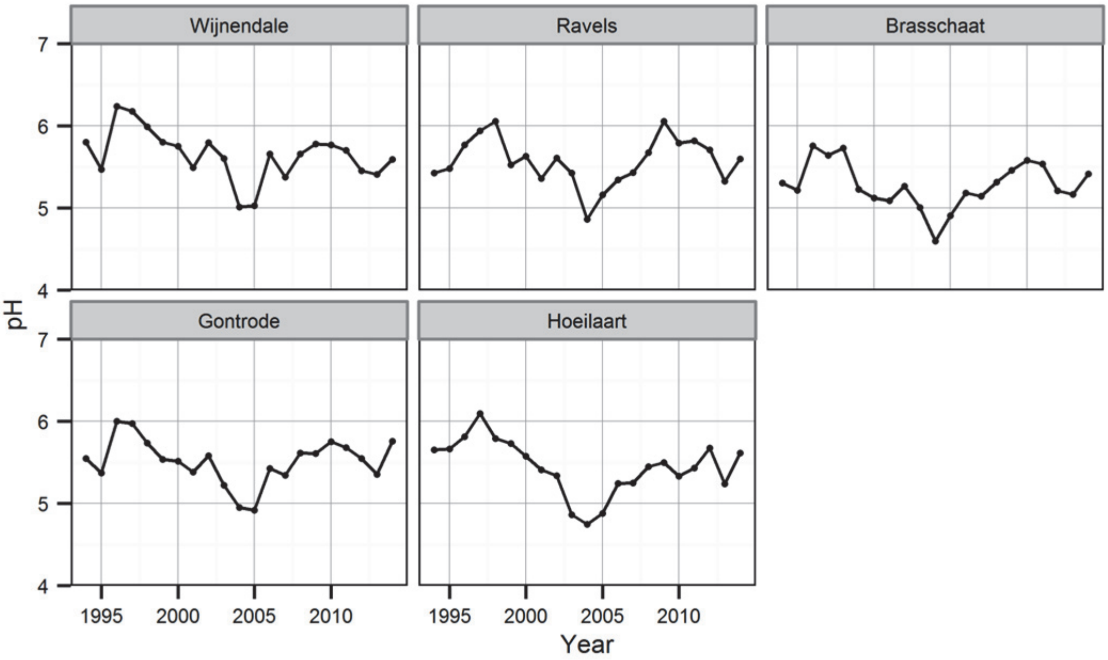

Figure 22 Mean annual pH of precipitation in the open field (1994–2014).

The concentration of SO_4^{2-} in precipitation showed a general and strong decreasing trend between 1994 and 2014, with a mean annual decrease of 0.06–0.07 mg L^{-1} (Table 7, Figure 23). The concentration of NH_4^+ in precipitation samples also showed a general decreasing trend between 1994 and 2014, with a mean annual decrease of 0.03–0.05 mg L^{-1}. The concentration of NO_3^- showed a much lesser mean annual decrease of 0.005–0.010 mg L^{-1}. The largest part of this decrease took place during the first year, while NO_3^- concentrations remained nearly stable thereafter. Also in 2014 NH_4^+ was still the most important N pollutant, but the NH_4^+:NO_3^- ratio decreased significantly during the monitoring period, except in RAV.

Table 7 Mann-Kendall trends for pollutant concentrations (mg L–1) in precipitation in the open field with slope and significance (ns: not significant, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

Plot	SO_4^{2-}	NH_4^+	NO_3^-	NH_4^+:NO_3^-
Wijnendale	–0.06***	–0.03***	–0.005**	–0.04***
Ravels	–0.06***	–0.03**	–0.010***	ns
Brasschaat	–0.06***	–0.04***	–0.009**	–0.03*
Gontrode	–0.07***	–0.04***	–0.010***	–0.03**
Hoeilaart	–0.06***	–0.05***	–0.005*	–0.06***

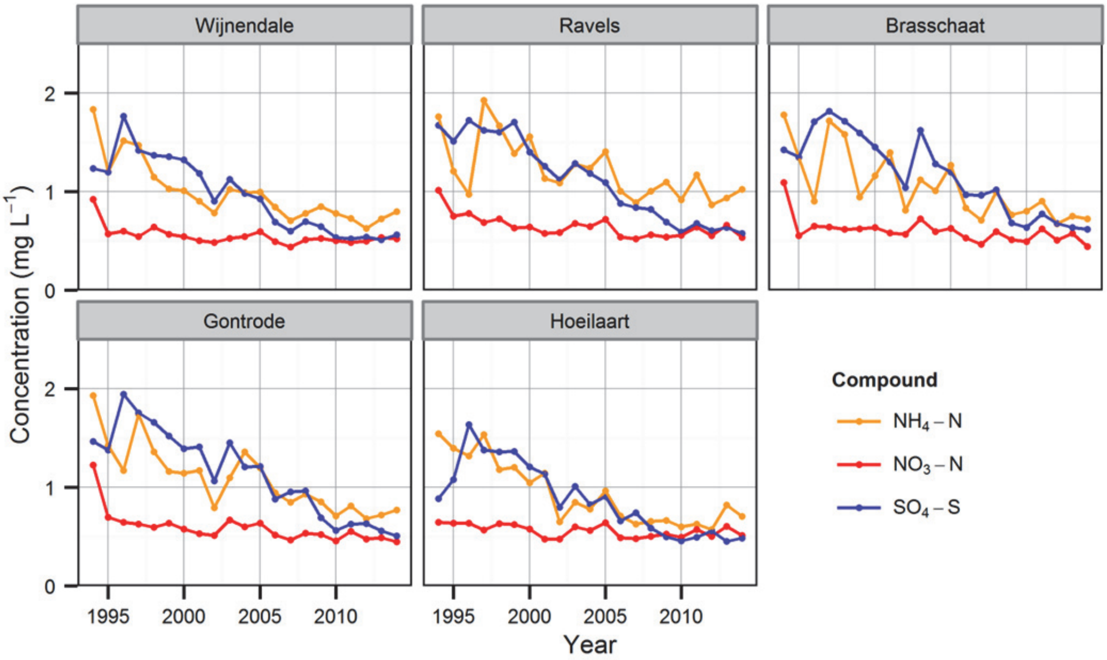

Figure 23 Mean annual concentrations (mg L^{-1}) of N and S compounds in precipitation in the open field (1994–2014).

The deposition of SO_4^{2-} through precipitation in the open field showed a general decreasing trend between 1994 and 2014, with a mean annual decrease of 0.03–0.04 $kmol_c$ ha^{-1} y^{-1} (Table 8, Figure 24). Also the deposition of NH_4^+ in the open field showed a general decreasing trend, with a mean annual decrease of 0.02–0.03 $kmol_c$ ha^{-1} y^{-1}. The deposition of NO_3^- decreased only in Ravels, Brasschaat and Gontrode, and at a much lower rate of 0.006–0.009 $kmol_c$ ha^{-1} y^{-1}. Acidifying depositions in the open field decreased at all plots by 0.06–0.08 $kmol_c$ ha^{-1} y^{-1}. In all plots, except in Ravels, the decrease in acidifying depositions was partially counterbalanced by a parallel decrease of base cation depositions, by 0.01–0.02 $kmol_c$ ha^{-1} y^{-1}.

Table 8 Mann-Kendall trends for deposition (kmol$_c$ ha^{-1} y^{-1}) of acidifying compounds (ACID = SO_4^{2-} + NH_4^+ + NO_3^-) and base cations (Ca^{2+} + K^+ + Mg^{2+}) through precipitation in the open field with slope and significance (ns: not significant, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

Plot	SO_4^{2-}	NH_4^+	NO_3^-	Base cations	ACID
Wijnendale	–0.03***	–0.02***	ns	–0.01*	–0.06***
Ravels	–0.03***	–0.03***	–0.006*	ns	–0.07***
Brasschaat	–0.04***	–0.03***	–0.009**	–0.02**	–0.08***
Gontrode	–0.04***	–0.03***	–0.008***	–0.01*	–0.08***
Hoeilaart	–0.03***	–0.03***	ns	–0.02*	–0.06***

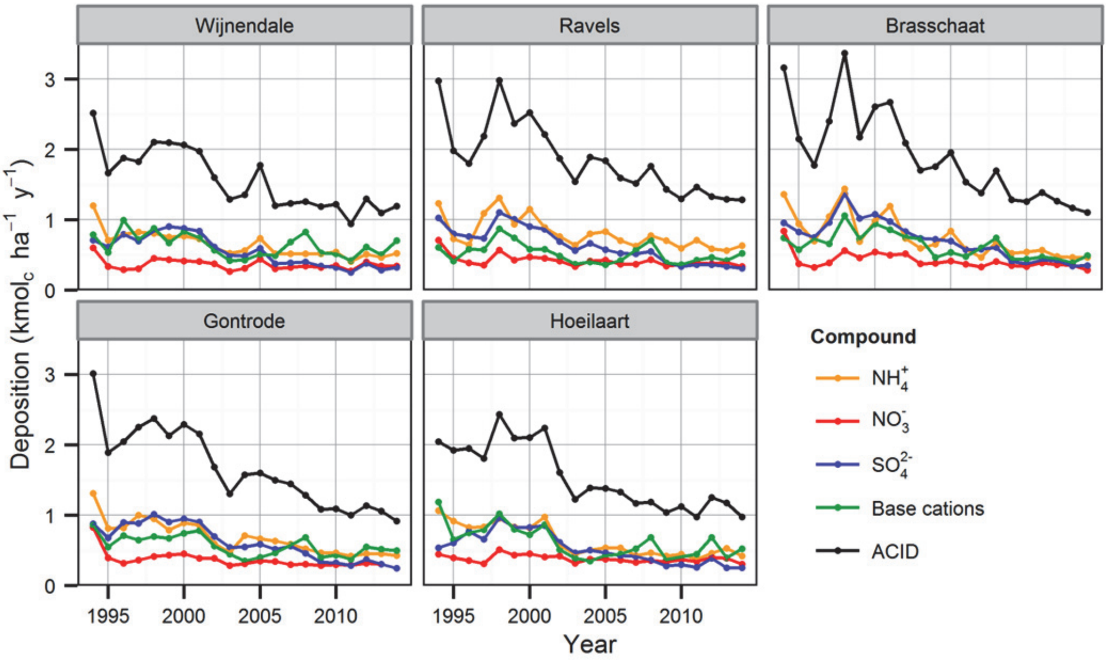

Figure 24 Annual deposition (kmol$_c$ ha^{-1} y^{-1}) through precipitation in the open field of NH_4^+, NO_3^-, SO_4^{2-}, base cations (Ca^{2+} + K^+ + Mg^{2+}) and acidifying deposition (ACID = SO_4^{2-} + NH_4^+ + NO_3^-) (1994–2014).

2.5.1.2 Throughfall

The pH of throughfall showed no clear trend over the monitoring period. But if we look more in detail, there is a similar pattern as for precipitation in the open field, with a generally decreasing pH of throughfall during the first years (1994–2004) and an increase thereafter (Figure 25).

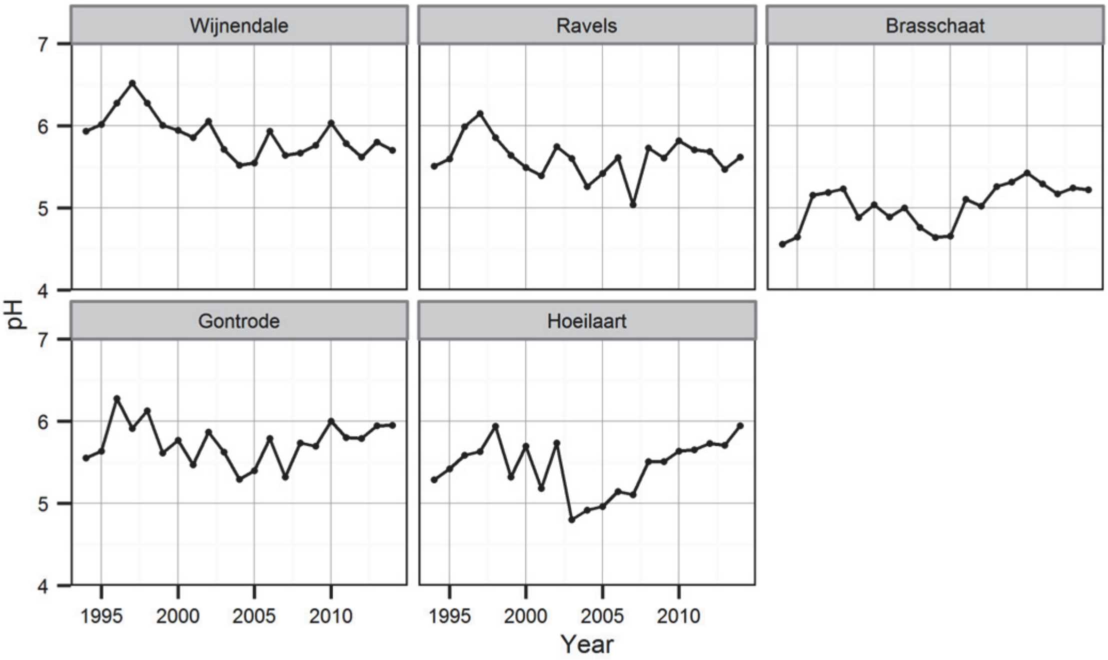

Figure 25 Mean annual pH of throughfall (1994–2014).

The concentrations of SO_4^{2-} in throughfall showed a general and strong decreasing trend between 1994 and 2014, with a mean annual decrease of 0.12–0.22 mg L^{-1} (Table 9, Figure 26). The concentrations of NH_4^+ in throughfall showed a similar general decreasing trend between 1994 and 2014, with a mean annual decrease of 0.08–0.18 mg L^{-1}. The concentrations of NO_3^- in throughfall did not change in Wijnendale and Gontrode and showed a minor decrease of 0.01–0.03 mg L^{-1} at the other plots. The NH_4^+:NO_3^- ratio in throughfall decreased significantly during the monitoring period, but NH_4^+ still remained the most important N pollutant in throughfall in 2014.

Table 9 Mann-Kendall trends for pollutant concentrations (mg L^{-1}) in throughfall with slope and significance (ns: not significant, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

Plot	SO_4^{2-}	NH_4^+	NO_3^-	NH_4^+:NO_3^-
Wijnendale	–0.12***	–0.12***	ns	–0.09***
Ravels	–0.22***	–0.18***	–0.02*	–0.09***
Brasschaat	–0.16***	–0.10***	–0.01*	–0.05***
Gontrode	–0.14***	–0.09***	ns	–0.07***
Hoeilaart	–0.13***	–0.08***	–0.03***	–0.03***

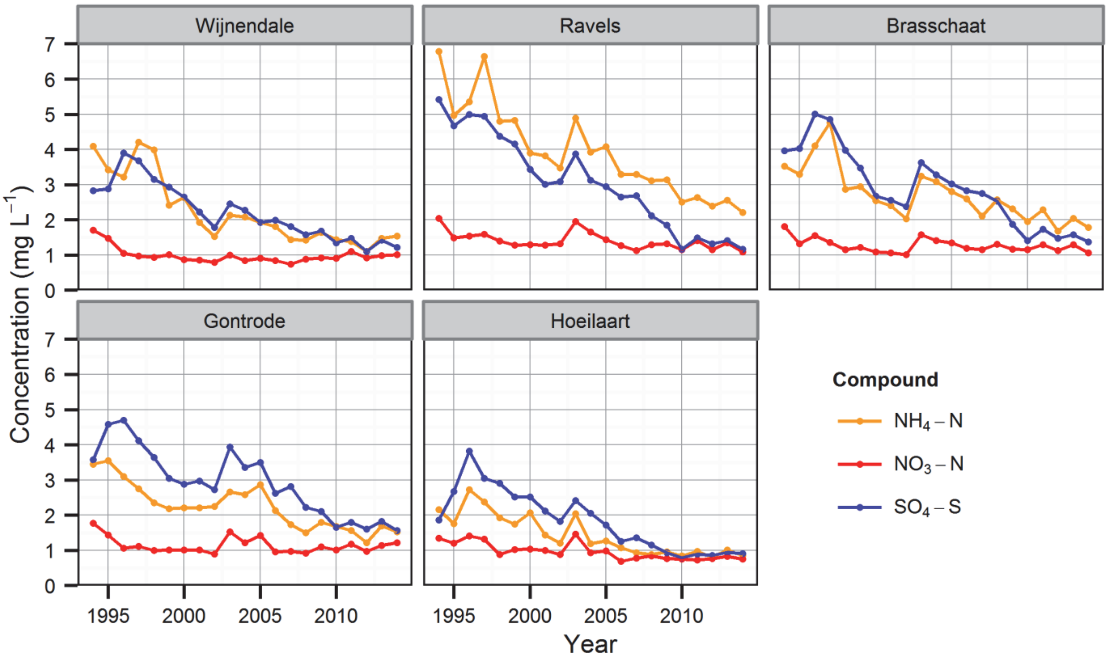

Figure 26 Mean annual concentrations (mg L^{-1}) of N and S compounds in throughfall (1994–2014).

2.5.1.3 *Stand deposition*

The deposition below canopy or stand deposition (throughfall + stemflow) of SO_4^{2-}showed a general decreasing trend between 1994 and 2014, with a mean annual decrease of 0.05–0.07 $kmol_c\ ha^{-1}\ y^{-1}$ (Table 10, Figure 27). Also the stand deposition of NH_4^+ showed a general decreasing trend, with a mean annual decrease of 0.04–0.07 $kmol_c\ ha^{-1}\ y^{-1}$. The stand deposition of NO_3^- decreased only in Brasschaat, Gontrode and Hoeilaart, at a much lower rate of 0.005–0.010 $kmol_c\ ha^{-1}\ y^{-1}$. The stand deposition of acidifying compounds decreased at all plots by 0.10–0.13 $kmol_c\ ha^{-1}\ y^{-1}$. In Brasschaat, Gontrode and Hoeilaart the decrease in acidifying stand deposition was partially counterbalanced by a parallel decrease of base cation deposition, by 0.02–0.04 $kmol_c\ ha^{-1}\ y^{-1}$. More details about the trends in stand deposition of acidifying compounds (1994–2010) in the five ICP Forests Level II plots in Flanders can be found in Verstraeten et al. (2012).

It should be remarked that the total deposition of acidifying compounds is in fact higher than the stand deposition, due to canopy exchange (uptake and leaching).

Table 10 Mann-Kendall trends for stand deposition (throughfall + stemflow) ($kmol_c\ ha^{-1}\ y^{-1}$) of total acidifying compounds (ACID = $SO_4^{2-} + NH_4^+ + NO_3^-$) and base cations ($Ca^{2+} + K^+ + Mg^{2+}$) with slope and significance (ns: not significant, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

Plot	SO_4^{2-}	NH_4^+	NO_3^-	Base cations	ACID
Wijnendale	–0.05***	–0.06***	ns	ns	–0.12***
Ravels	–0.07***	–0.07***	ns	ns	–0.13***
Brasschaat	–0.07***	–0.05***	–0.005**	–0.02***	–0.13***
Gontrode	–0.07***	–0.05***	–0.007***	–0.03**	–0.13***
Hoeilaart	–0.06***	–0.04***	–0.010***	–0.04**	–0.10***

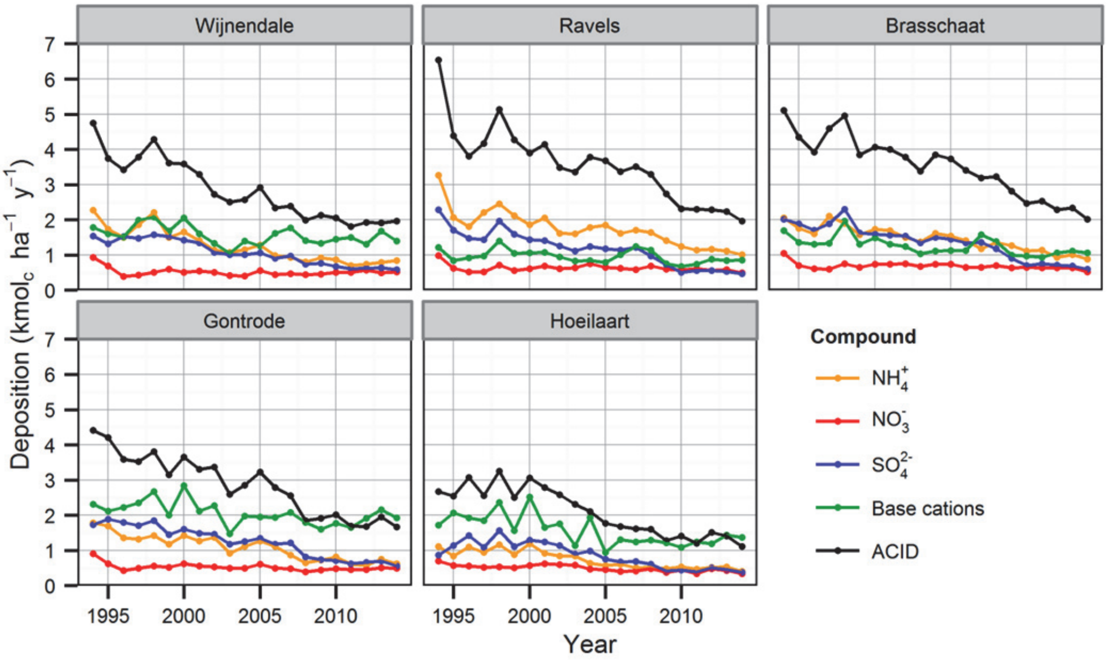

Figure 27 Annual stand deposition (throughfall + stemflow) (kmol$_c$ ha^{-1} y^{-1}) of NH_4^+, NO_3^-, SO_4^{2-}, base cations (Ca^{2+} + K^+ + Mg^{2+}) and total acidifying deposition (ACID = SO_4^{2-} + NH_4^+ + NO_3^-) (1994–2014).

2.5.2 Soil solution

2.5.2.1 Concentrations of N and S compounds

The concentrations of SO_4^{2-} in soil solution showed an overall decreasing trend during the monitoring period, while the concentrations of NO_3^- showed decreasing trends at four plots, but not in Gontrode (Figure 28). The concentrations of NH_4^+ were low in the O horizon and usually below the LOQ in the mineral soil. More details about the trends in N and S compounds (1994–2010) in the soil solution of the five ICP Forests Level II plots in Flanders can be found in Verstraeten et al. (2012).

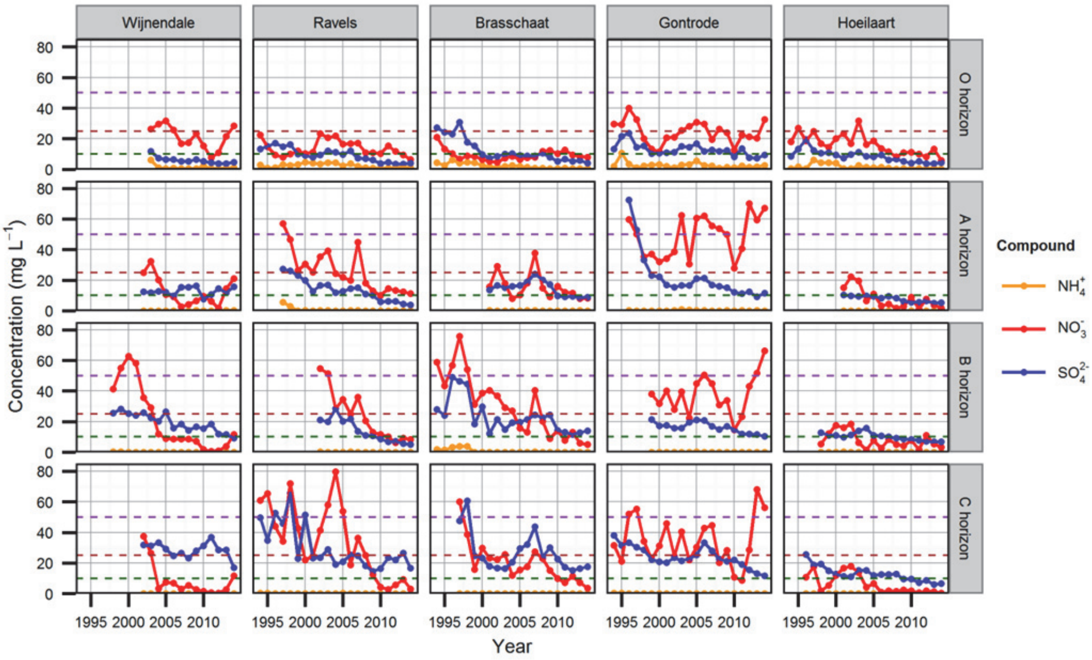

Figure 28 Mean annual concentrations (mg L^{-1}) of N and S compounds in the soil solution (1994–2014). Dashed lines: Drinking Water Directive (98/83/EC) maximum allowable level (purple) guide level (brown) and background level (green) for NO_3^- concentration.

2.5.2.2 pH

The pH of the soil solution initially decreased in most plots and at most depths. During the past decade, the pH showed a weak but significant recovery in the mineral soil of all plots and in the organic layer of Wijnendale, Brasschaat and Hoeilaart (Figure 29). More details about the trends in soil solution pH (1994–2010) at the five ICP Forests Level II plots in Flanders can be found in Verstraeten et al. (2012, 2016).

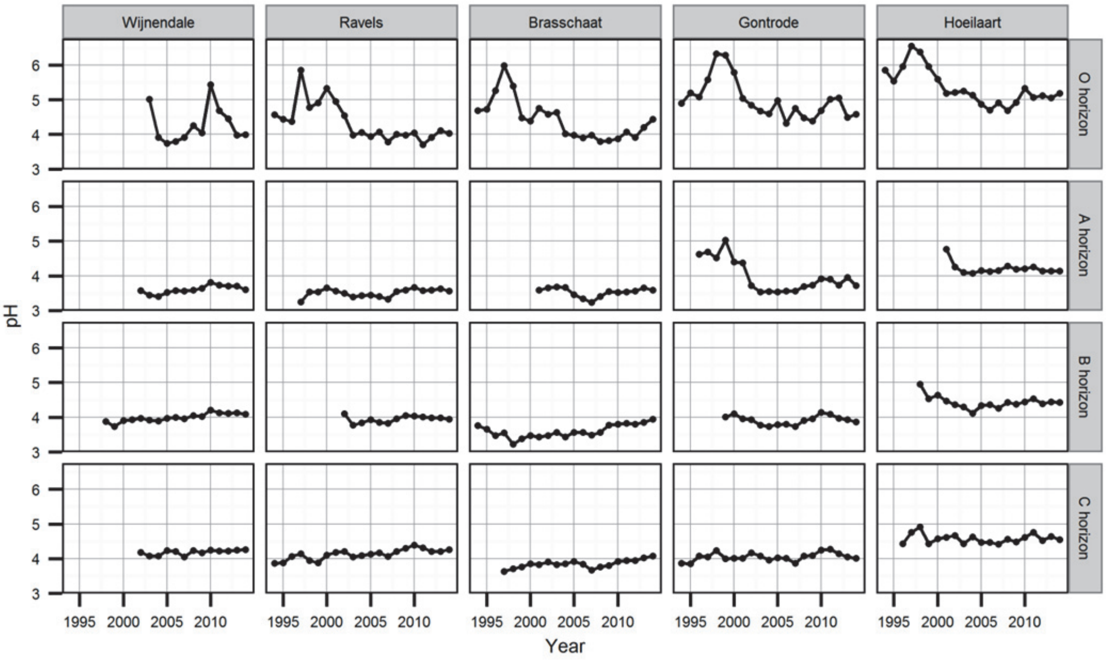

Figure 29 Mean annual pH of the soil solution (1994–2014).

2.5.2.3 Bc:Al ratio

The base cations (Bc = Ca^{2+} + K^+ + Mg^{2+}) to aluminium (Al) ratio, Bc:Al (mol/mol) in the soil solution initially decreased in all plots during the monitoring period, but recovered slightly in Brasschaat and Gontrode during the past decade, while a further decrease was observed in Wijnendale, Ravels and Hoeilaart (Figure 30). More details about the trends in Bc:Al ratio (1994−2010) in the soil solution of the five ICP Forests Level II plots in Flanders can be found in Verstraeten et al. (2012).

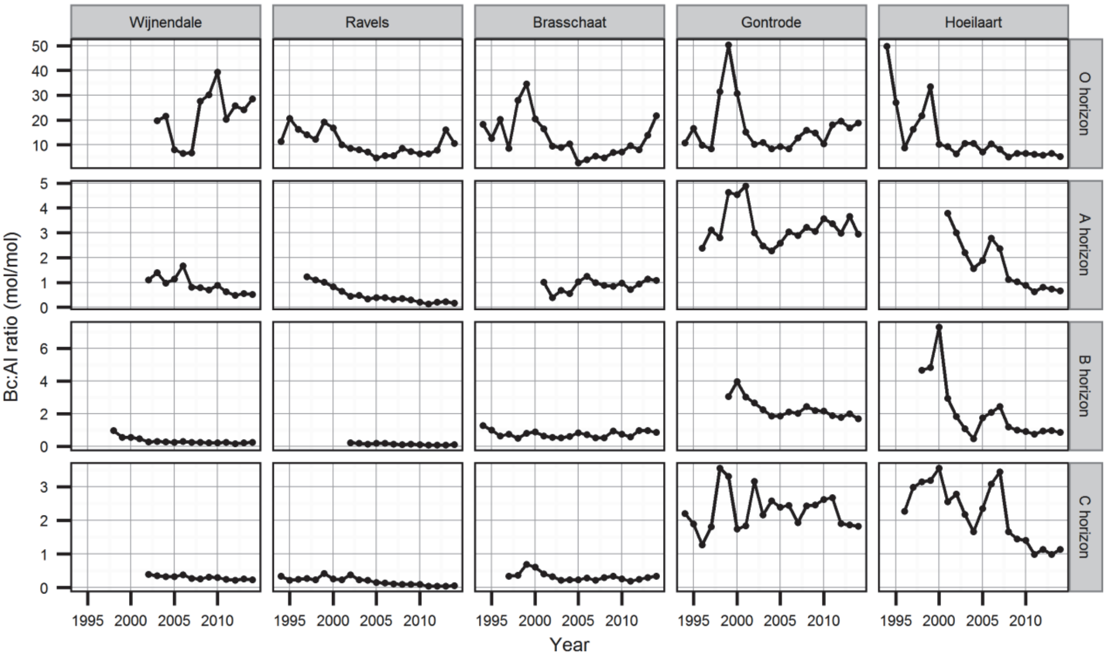

Figure 30 Base cations (Ca^{2+} + K^+ + Mg^{2+}) to aluminium ratio (Bc:Al) in the soil solution.

2.5.2.4 Acid neutralizing capacity (ANC)

The ANC of the soil solution (calculated as Ca^{2+} + K^+ + Mg^{2+} + Na^+ - Cl^- - SO_4^{2-} - NO_3^- - NH_4^+) showed increasing trends at all depths in Wijnendale, Ravels and Brasschaat, indicating that soil acidification is slowing down in these plots (Figure 31). In Hoeilaart and Gontrode, an increasing trend of ANC was observed in the organic layer, even with clearly positive values in Hoeilaart, while the ANC in the mineral soil was nearly stable but flirted with zero.

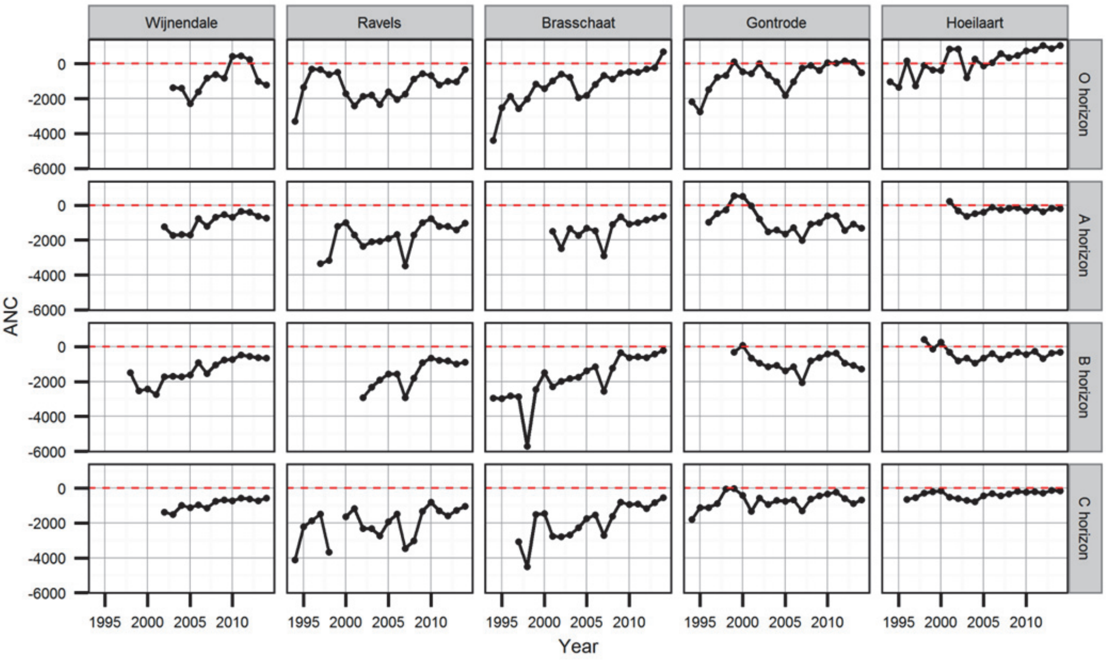

Figure 31 Acid neutralizing capacity (ANC) of the soil solution.

2.5.3 Foliar concentrations

Foliar nutrient concentrations in the 5 intensive forest monitoring plots are analysed biannually, in order to describe the nutritional status of the trees and to assess changes in tree nutrition. In each plot 5 permanently marked trees are sampled. Nitrogen is one of the key elements here, because it was the limiting nutrient for tree growth in many forest ecosystems for a long time. However, decades of high atmospheric N deposition in Flanders have resulted in a considerable nitrogen enrichment, which is reflected in N concentrations in leaves and needles of forest trees.

In 1995–2013 the foliar nitrogen status in the 2 beech plots is high. The highest concentrations are found in Wijnendale forest (Figure 32), but also in the beech plot at the Zoniën forest N foliar concentrations are evaluated as ‘surplus – luxury’ (23.2–27.5 mg g^{-1}) according to the foliar nutrient thresholds by Mellert & Göttlein (2012).

The same applies to common oak, with high ‘surplus – luxury’ N concentrations in the Aelmoeseneie forest at Gontrode. The average nitrogen foliar concentration in this plot increased almost continuously from 25582 mg kg^{-1} in 1995 until 29220 mg kg^{-1} in 2007, followed by a limited decrease.

The nitrogen concentrations in current year Scots pine needles at Brasschaat were high at the start of the monitoring project (‘surplus – luxury’ or even ‘surplus – extreme’ in 1999). Though since then, a gradual decrease could be observed (Figure 32). In 2013, for the first time, the nitrogen concentrations were evaluated as ‘normal – upper range’.

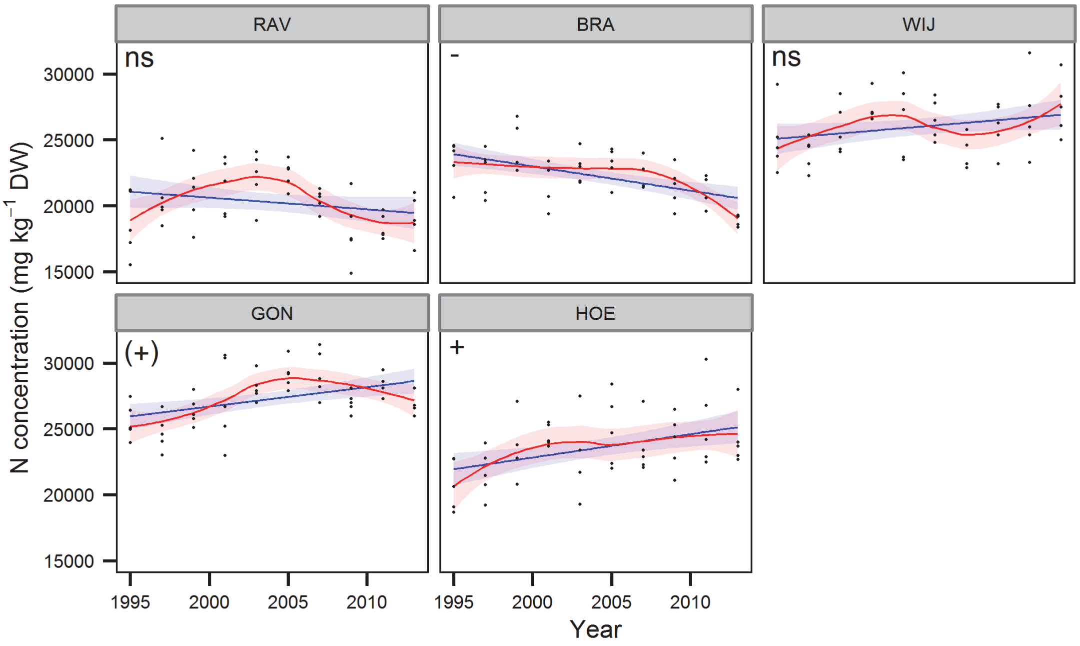

Figure 32 Nitrogen concentrations (mg kg^{-1} Dry Weight) in leaves of beech, common oak, Scots pine and Corsican pine at 5 intensive monitoring plots (RAV = Ravels, BRA = Brasschaat, WIJ = Wijnendale, GON = Gontrode, HOE = Hoeilaart). Blue = linear regression line and its 95% confidence interval; Red = loess curve and its 95% confidence interval.

2.5.4 Seed production of common oak and European beech

Since the start of measurements in 1999 we observed massive seed production (mast years) of common (pedunculate) oak (*Quercus robur* L.) and European beech (*Fagus sylvatica* L.) every two to three years (Figure 33). In 2013–2014 we observed, for the first time, two subsequent years with massive seed production of beech. This was the case in Hoeilaart and Wijnendale, but not in Wijnendale, perhaps because a thinning had been conducted during the preceding summer in this plot. In Europe, the masting frequency of beech is increasing, but the trend in Flanders is not significant (Nussbaumer et al., 2016).

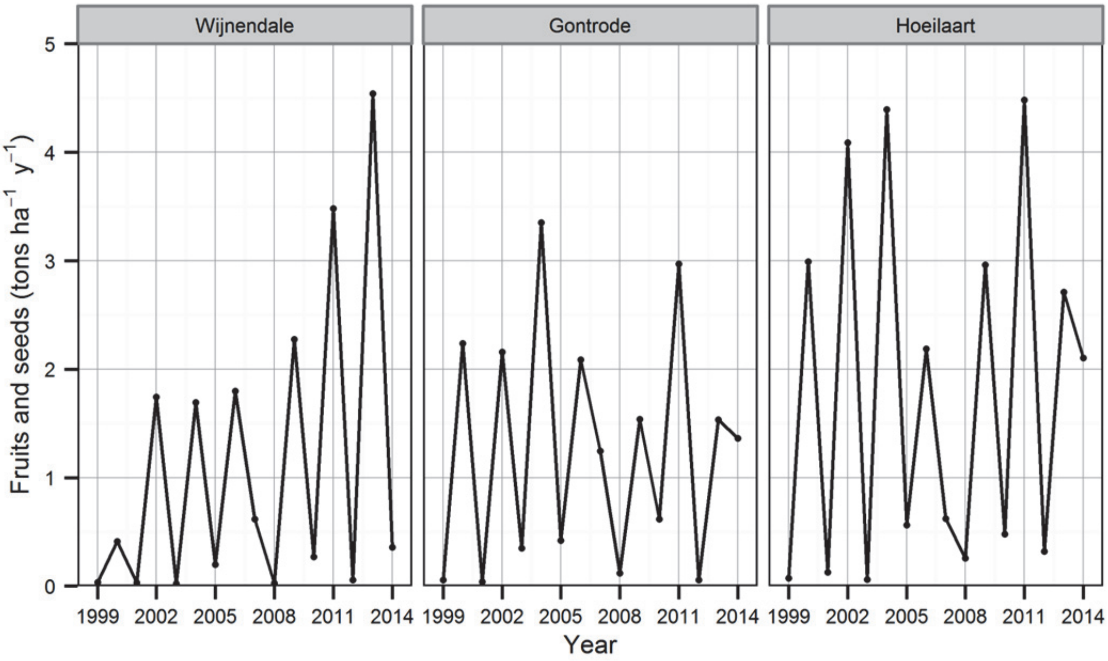

Figure 33 Annual production of fruits and seeds including seed capsules (tons ha^{-1} y^{-1}) in the Level II core plots in deciduous forest (European beech in Wijnendale en Hoeilaart, a mixture of common oak and European beech in Gontrode).

2.5.5 Air quality

2.5.5.1 Meteorological measurements at Brasschaat

Material and methods

Measurements of atmospheric gaseous pollutants and meteorological conditions have been carried out at the tower since mid-1995. Meteorological data include vertical profiles of air temperature and humidity (HMP 230 dew point transmitter and PT100, Vaisala, Finland) in aspirated radiation shields at 2, 24 and 40 m height (Figure 34). Wind speed measurements (LISA cup anemometer, Siggelkow GMBH, Germany) are conducted at 24, 32 and 40 m height. At the top of the tower, ingoing and outgoing short-wave and long-wave radiation are measured by a CNR1-radiometer (pyranometer/pyrgeometer, Kipp and Zonen, the Netherlands) and a CMP6-pyranometer (Kipp and Zonen, the Netherlands). A wind vane (potentiometer W200P, Campbell, UK) is mounted on a tower rail. Rainfall is registered by a tipping bucket rain gauge (NINA precipitation pulse transmitter, Siggelkow GMBH, Germany). Throughfall is measured using a gutter system, with a total collection surface of ± 6 m^2, at two locations within the forest. Each gutter system consists of four 7 m long gutters, which are connected to a 0.25 L tipping bucket (with pulse transmitter). All meteorological sensors are sampled at 0.1 Hz and stored as half hour means on a data logger (Campbell CR1000, UK).

Figure 34 Tipping bucket for rainfall measurement on top of the tower (upper left), gutter system for throughfall measurement (upper right), wind speed anemometer mounted on a boom (lower left) and relative humidity/temperature sensors fixed inside aspirated radiation shields (lower right).

Meteorological measurements 2012−2014

A marked interannual variability was recorded with regard to temperature and precipitation (Table 11). During 2014, the yearly average temperature amounted to 11.8 degrees Celsius, which was close to the values of the measuring years 2003 (11.7 °C), 2005 and 2006 (11.9 °C in both years). In 2013, on the contrary, the annual average temperature dropped below 10°C, which was due to a long winter. Average monthly temperature in March 2013 amounted to 2.7 °C, which was much lower compared to the March temperatures recorded in 2012 (8.6 °C) and 2014 (9.3 °C). Since the onset of the measurements in 1995, such a low annual temperature was only measured in 1996 (8.8 °C) and 2010 (9.2 °C).

During 2012, the highest amounts of rainfall (tipping bucket) and throughfall (gutters) were measured (resp. 908 and 733 mm). The ratio of throughfall to precipitation averaged 80% on annual basis. The ratio tended to decrease during the growing season (Figure 35). This could be partly attributed to a higher plant area index and a higher evaporation rate of the intercepted rain water during the growing season. It must be emphasized that also other factors such as wind speed and rainfall intensity do have an impact on the ratio of throughfall to precipitation (not in figure).

Table 11 Overview of the monthly average temperature (T), relative humidity (RH), air pressure (Pair), solar radiation (SUN), monthly rainfall (R) and throughfall amount (TF) at Brasschaat during the measuring years 2012, 2013 en 2014.

YEAR	*T (°C)*	*RH (%)*	*Pair (hPa)*	*SUN (W/m²)*	*R (mm)*	*TF (mm)*
2012	**10.4**	**78.7**	**1016.2**	**117.8**	**908.2**	**733.3**
1	5.1	85.4	1021.2	29.0	98.5	70.4
2	0.6	81.8	1029.6	64.2	26.7	21.5
3	8.6	78.3	1027.7	117.4	24.9	23.0
4	8.2	76.5	1006.0	138.0	75.4	50.5
5	14.1	71.1	1016.3	216.6	46.0	32.7
6	15.1	73.1	1013.5	190.0	120.5	98.2
7	17.0	74.5	1014.9	187.5	118.5	94.4
8	18.8	70.3	1016.2	195.7	48.7	34.7
9	14.5	73.3	1016.1	143.3	59.0	44.6
10	10.8	82.6	1011.7	77.0	92.8	76.3
11	7.0	87.7	1011.9	35.5	35.8	30.6
12	5.0	89.6	1010.1	21.4	161.5	156.4
2013	**9.9**	**77.5**	**1016.1**	**115.4**	**781.4**	**631.6**
1	1.9	87.5	1015.1	29.6	51.5	50.9
2	1.5	83.7	1017.4	51.6	38.3	32.7
3	2.7	70.0	1009.7	99.1	23.9	23.3
4	8.5	66.6	1016.0	165.8	27.0	18.4
5	11.0	76.8	1012.3	170.3	110.9	86.2
6	15.3	72.1	1018.7	200.7	49.6	35.0
7	19.5	70.7	1020.4	225.2	60.9	43.6
8	18.4	70.3	1018.3	177.3	24.1	16.2
9	14.5	78.7	1016.0	127.5	116.7	95.6
10	12.5	83.6	1013.8	72.9	110.0	93.1
11	6.6	88.2	1016.7	30.9	109.0	93.3
12	6.1	82.7	1018.6	30.1	59.5	43.3
2014	**11.8**	**77.0**	**1014.3**	**116.4**	**838.2**	**614.3**
1	6.0	82.7	1006.5	30.3	73.7	50.4
2	6.5	78.5	1004.3	54.9	76.9	50.1
3	9.3	67.2	1017.1	124.3	20.0	13.9
4	12.4	67.7	1015.5	167.6	10.3	5.1
5	13.4	69.9	1016.0	191.7	77.3	55.3
6	16.0	68.8	1019.2	223.7	47.8	29.3
7	19.1	75.2	1015.0	191.7	116.0	85.5
8	15.9	77.3	1012.7	150.8	174.3	127.4
9	16.3	79.0	1019.4	131.1	23.1	15.8
10	13.4	83.6	1015.3	68.1	89.0	72.4
11	8.5	87.1	1010.5	41.0	48.7	39.7
12	4.7	86.9	1019.0	18.6	81.2	69.4

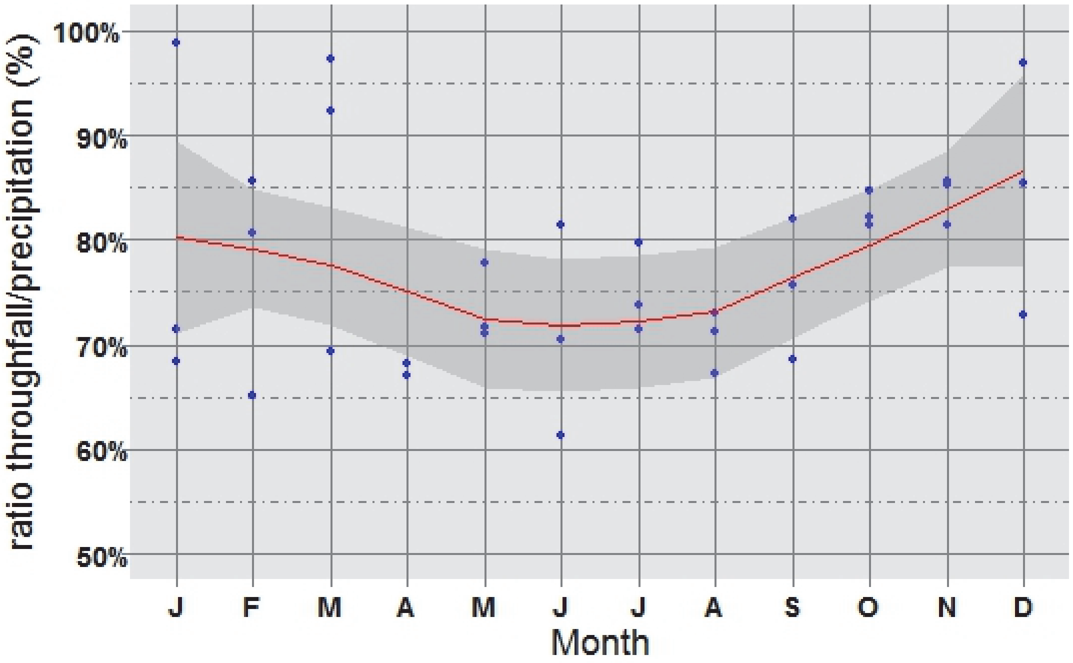

Figure 35 Monthly ratio of throughfall to precipitation during the measuring years 2012–2014 (months with monthly throughfall below 10 mm are not included).

The prevailing wind direction is WSW–SW (± 240 degrees, Figure 36). Lowest wind frequency occurs in the northern and southeastern wind sectors. Average wind speed at 40 m height amounts to 3.3 m s^{-1}, with highest average wind speeds (> 4 m s^{-1}) being reached in the WSW–SW wind sector. Half hourly wind speeds in this wind sector attained maximum values of 11 till 13 m s^{-1}. Within the half hourly time record, gusts of wind may reach maximum speeds over 30 m s^{-1}.

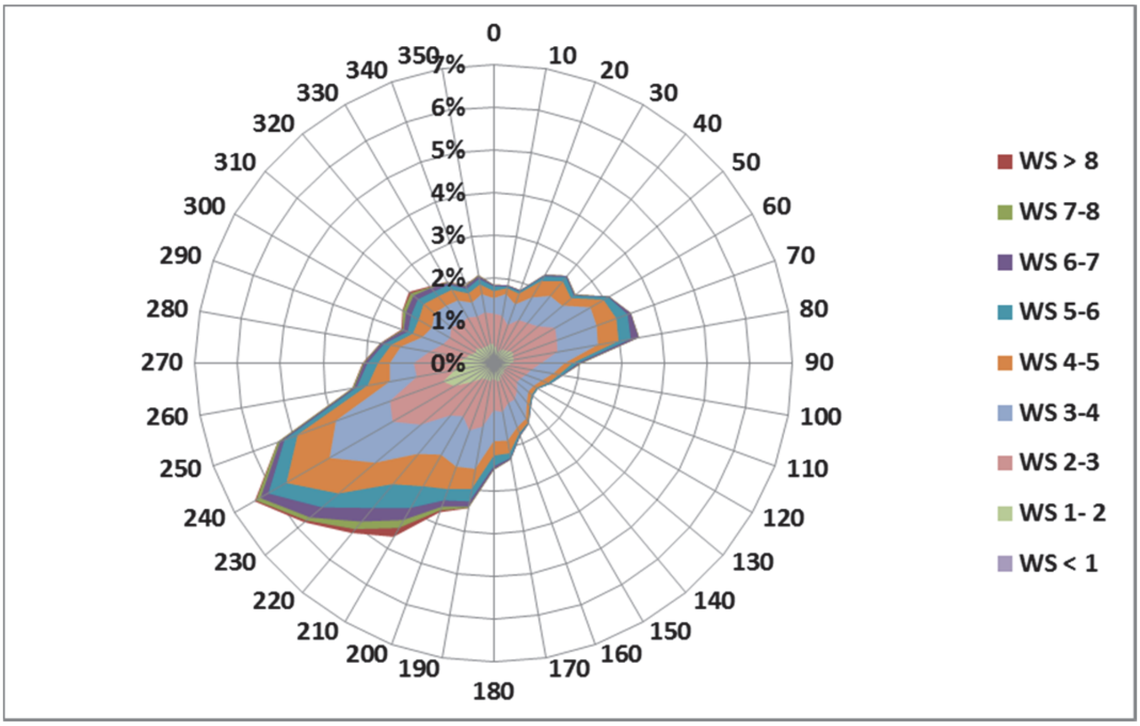

Figure 36 Relative distribution of the wind speeds (40 m height) and wind directions at Brasschaat (% per wind direction class of 10 degrees). Legend represents the wind speed binned into classes of 1 m s^{-1}.

2.5.5.2 SO_2, O_3 and NO_x measurements at Brasschaat

Materials and methods

Vertical profiles of SO_2, O_3 and NO_x concentrations are being measured at two inlets above the canopy (at 24 and 40 m) using an UV-fluorescence (TEI 43C, Thermo Environmental Instruments), an UV Photometric Analyzer (model TEI 49I, Thermo Environmental Instruments) and a Chemiluminescence monitor (Ecophysics, CLD 700 AL), respectively.

From each inlet, air is drawn through 53.5-m-long Teflon sampling tubes (Figure 37) with a flow rate of 60 l min^{-1} and led towards an air conditioned instrument shelter perched on the concrete base of the scaffolding. Prior to transport, air is filtered through 0.5 mm Teflon filter housings, which are covered with a rain shield and mounted at the end of a 1.5 m long boom. The Teflon tubings (external diameter 9.5 mm) are wrapped with 47-mm-isolated housings and heated to 35 °C using an electric heating wire. Each inlet is sampled for 5 min before switching to the next inlet using a PLC controlled valve system. An additional filter of 0.5 µm is placed before the sample inlet from the monitor. Readings of the first minute from every inlet are discarded as sample tubes need to be flushed and monitors need to be stabilized.

Figure 37 Air is drawn through teflon filter housings covered with a rain shield.

Results 2012−2014

Highest concentrations of SO_2 (8 µg m^{-3}) are measured when winds blow from the west. In these conditions, SO_2 bearing air masses, mainly originating from the petrochemical industry located at Antwerp port, are transported over the forest (Figure 38). The presence of some sulphur-rich clay processing brickyards, located eastwards of the site, are possibly contributing to elevated SO_2 concentrations in the eastern sector of the pollution rose. Southern and northern winds are carrying the lowest amounts of sulphur.

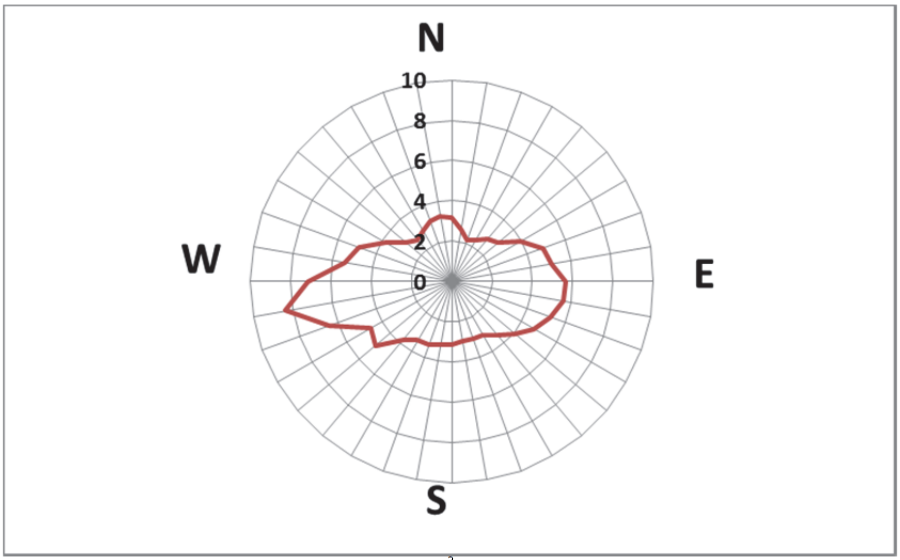

Figure 38 Pollution rose of SO_2 (units in µg m^{-3}).

Highest NO_x levels are measured in the southern as well as the western wind sector (Figure 39). In the latter wind sector, oil refineries constitute the main contributors to the NO_x emissions (http://www.lne.be/themas/luchtverontreiniging/nieuwactieplanantwerpen-2014-2018-goedgekeurd.pdf). High NO_x (NO) concentrations in the southern wind sector are especially due to vehicle emissions from the E19 highway and suburban traffic in the adjacent residential areas. Highest ozone concentrations are measured when the site is exposed to northern winds, which transport fewer amounts of NO, the main titrant of ozone. The intensity of pollution does not merely depend on exposure to a specific wind direction. Also other meteorological influences such as mixing conditions of the atmosphere (atmospheric stability), precipitation events, temperature and relative humidity affect the magnitude of the pollutant concentrations.

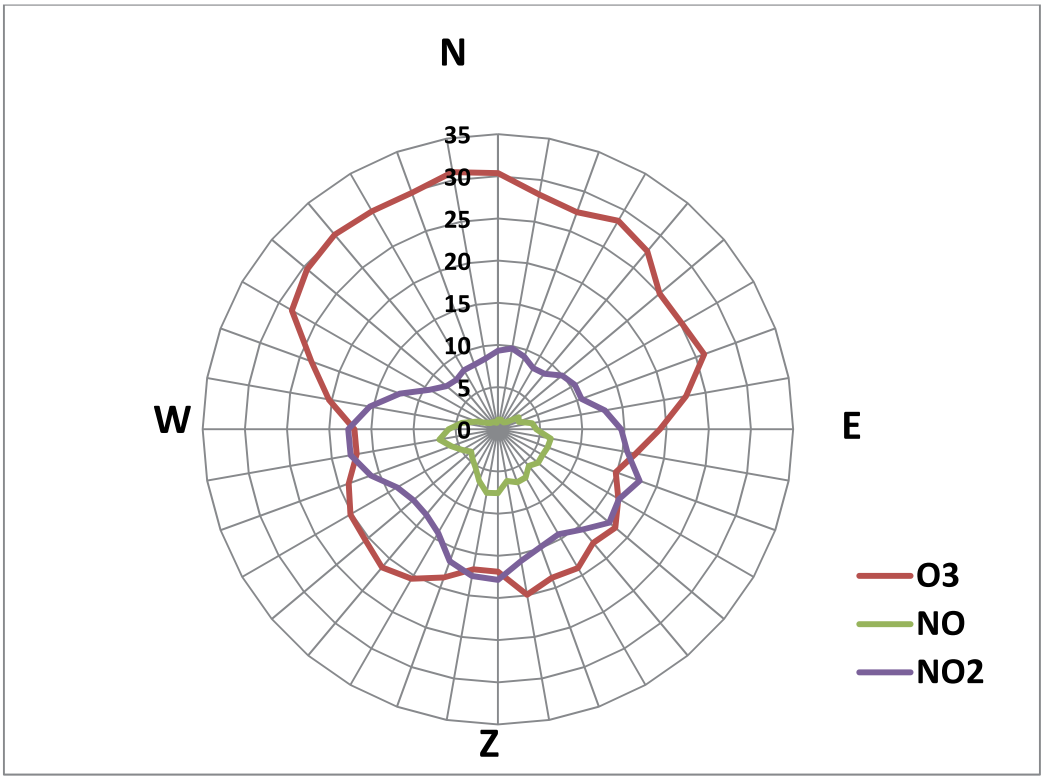

Figure 39 Pollution rose of the NO-NO_2-O_3 triad (units in ppb).

The decreasing sulphur emission from Antwerp harbour has resulted in a drop in annual SO_2 levels from 20 µg SO_2 m^{-3} in 1995 to 4 µg m^{-3} in 2014 (Figure 40). This is far below the annual critical level of 20 µg m^{-3}, established for forest ecosystems. Also NO_x concentrations have declined substantially over the last two decades, but concentrations still exceed the annual critical level of 30 µg m^{-3} (expressed as NO_2), established for semi-natural vegetation (CLRTAP, 2014). Moreover, the critical level of 75 µg m^{-3}, adopted for comparison with daily mean concentrations, was still frequently exceeded during the last years (> 40 days per year). Ozone concentrations, on the contrary, were subjected to increasing trends. Ozone indices, which are calculated to judge the risk for ozone damage, indicate that current levels could be harmful for forest trees (see 2.6.3.).

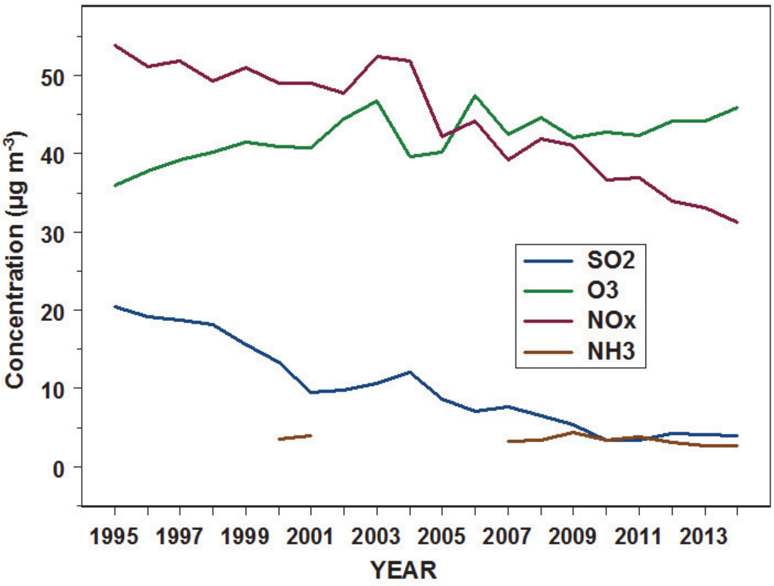

Figure 40 Two-decadal trends of air pollutants SO_2, O_3 and NO_x (in µg m^{-3}).

Median values of half-hourly SO_2, O_3 and NO_2 concentrations only differed slightly from their respective half-hourly averages (Table 12). This was also the case for the daily values (Table 12). Average half hourly and daily values of NO were, however, considerably larger than their respective median values, due to the distinct lognormal distribution of the latter pollutant.

Over the measuring period 2012-2014, half-hourly maxima of 73.9, 228.8, 403 and 201 µg m^{-3} were recorded for SO_2, O_3, NO and NO_2, respectively. For the daily concentrations, maxima were 29.7, 136.5, 122.6 and 91.2 µg m^{-3}, respectively (Table 13).

Table 12 Percentile distribution of half-hourly concentrations of SO_2, O_3, NO and NO_2 over the measuring period 2012−2014 (in µg m^{-3}).

	P10	*P30*	*P50*	*P60*	*P70*	*P80*	*P90*	*P95*	*P98*	*Max*	*Avg*
SO_2	0.4	1.8	3.2	3.9	4.7	6.1	8.6	11.3	15.2	73.9	4.1
O_3	3.7	26.5	44.1	52.2	60.0	69.1	82.4	95.0	112.8	228.8	44.8
NO	0.0	0.2	0.8	0.8	0.9	3.1	12.4	28.4	54.4	403.0	5.1
NO_2	7.0	13.0	20.1	24.9	30.9	38.9	50.7	60.9	72.5	201.0	25.1

Table 13 Percentile distribution of daily concentrations of SO_2, O_3, NO and NO_2 over the measuring period 2012–2014 (in µg m^{-3}).

	P10	*P30*	*P50*	*P60*	*P70*	*P80*	*P90*	*P95*	*P98*	*Max*	*Avg*
SO_2	1.0	2.4	3.6	4.3	4.9	5.9	7.7	9.4	11.3	29.7	4.1
O_3	14.5	32.4	45.6	51.3	57.6	64.0	73.0	80.0	85.5	136.5	44.9
NO	0.2	0.8	1.3	1.9	3.7	6.2	13.7	22.8	40.0	122.6	5.1
NO_2	10.1	17.1	23.2	26.5	30.1	35.6	42.7	49.7	56.3	91.2	25.1

For all pollutants, a distinct seasonal variation in concentration was noticed. For SO_2, NO and NO_2, pollutant concentrations tended to be higher during the winter (3-year seasonal mean of 5.3, 6.3 and 29.3 µg m^{-3}, respectively). During the summer half year, the 3-year seasonal mean concentrations were confined to 2.8, 2.4 and 20.1 µg m^{-3}, respectively. Ozone concentrations were more elevated during the summer half-year with a seasonal mean of 56.5 µg m^{-3} (compared to 32.6 µg m^{-3} as seasonal mean for winter half-year).

Formation of ozone is due to highly non-linear, mostly photochemical processes involving NO_x and volatile organic compounds. Nitric oxide is reacting with ozone to yield nitrogen dioxide and oxygen. Ozone concentrations were negatively correlated with its main titrant NO (Figure 41).

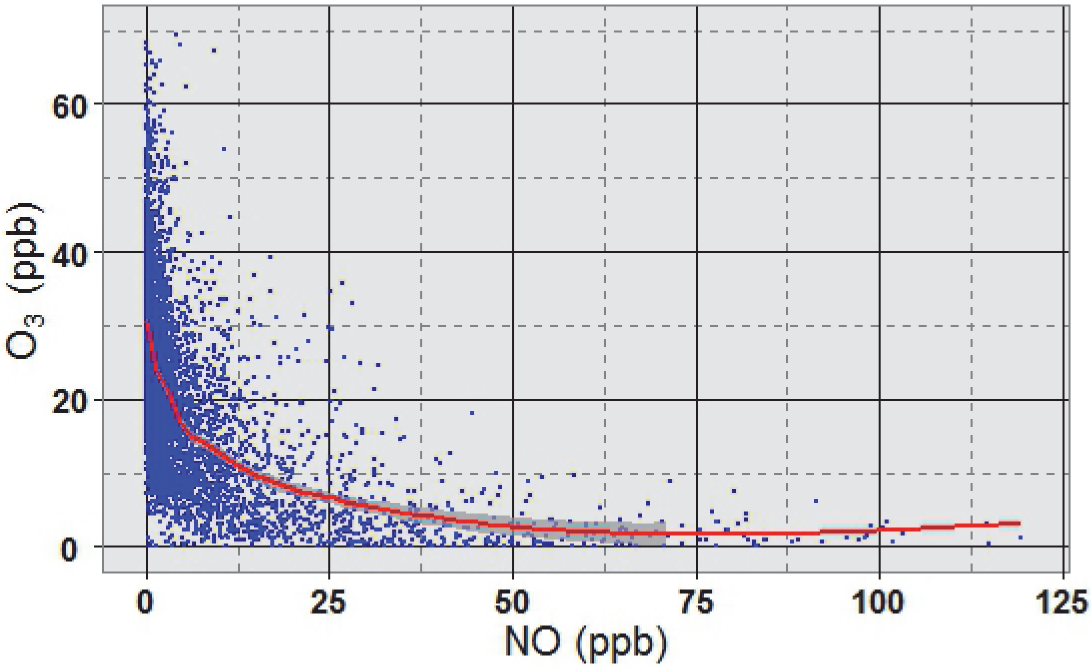

Figure 41 Relationship between halfhourly NO and O_3 concentrations during the period 2012–2014 (in ppb).

The O_3-NO-NO_2 triad is subjected to a marked diurnal cycle, which is further altered by season and the magnitude of traffic intensity (Figure 42–Figure 44). During the working week, a distinct morning peak in NO concentration is observed due to vehicle emissions during the rush hours. During the winter half-year (April-September), this peak is more pronounced and also a slight increase in concentration is shown in the evening hours. This cannot be observed during summer as more ozone is more readily available to react with nitric oxide. For NO_2, the traffic-related two-peaked diurnal course is also more conspicuous during the winter time (Figure 43).

During the weekend, however, NO_x emissions from traffic are drastically curbed leading to substantial lower concentrations. As a result, the air masses above the forest are much lower in NO_x concentrations and the diurnal course of NO and NO_2 is more flattened compared to working week conditions.

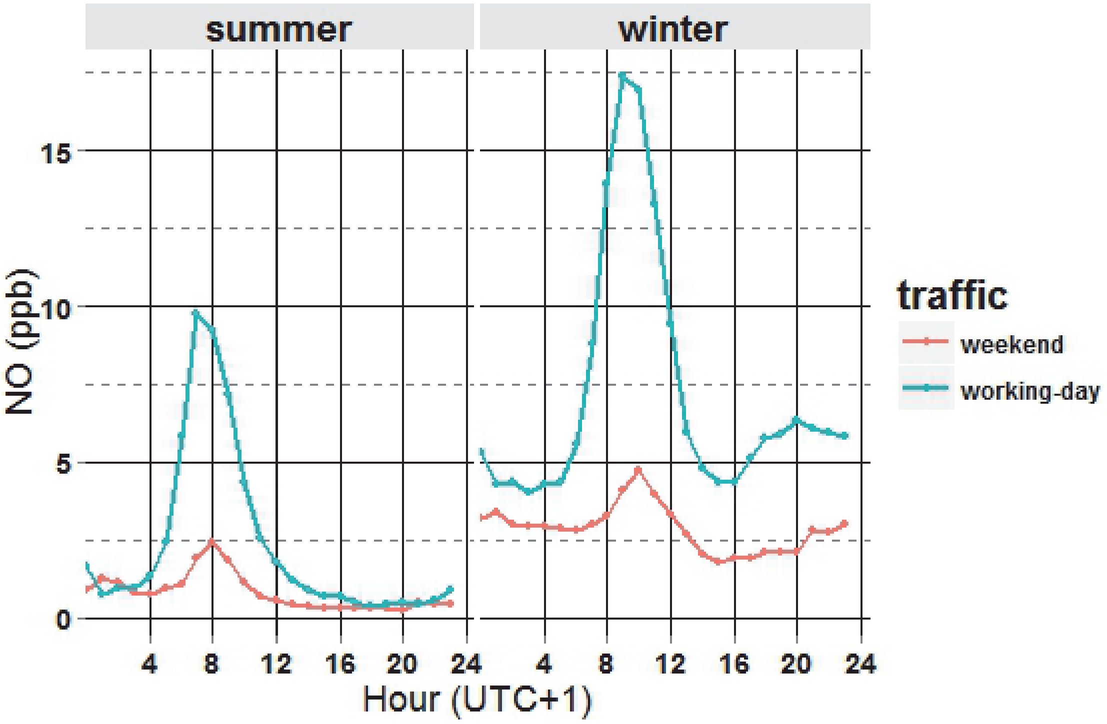

Figure 42 Diurnal course of NO during summer and winter half-year as affected by traffic volume over the 2012–2014 period (in ppb).

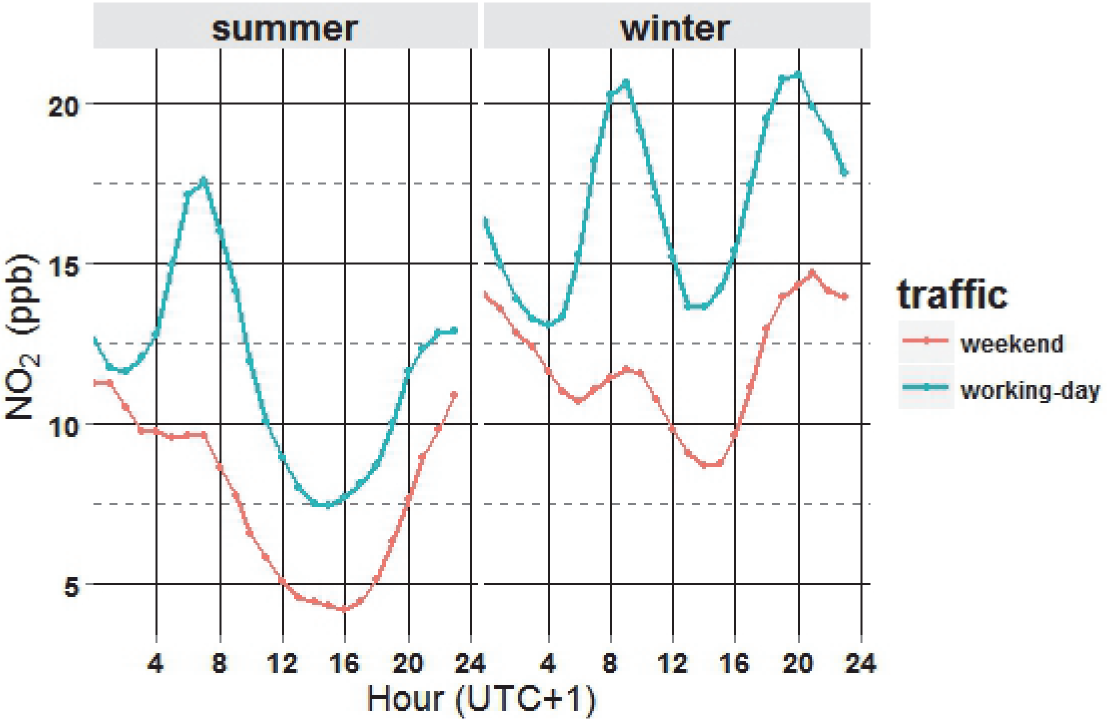

Figure 43 Diurnal course of NO_2 during summer and winter half-year as affected by traffic volume over the 2012–2014 period (in ppb).

The marked differences in NO_x emissions during the week and weekend clearly affect the measured ozone levels. During the relatively poor NO_x-weekends, the atmosphere is generally richer in ozone levels compared to working weeks (on average 5 ppb higher, $p < 0.0001$). Because working weeks generally entail higher NO levels, more titration takes place and hence a significant lowering of ozone levels occurs in areas adjacent to highways due to traffic (Figure 44).

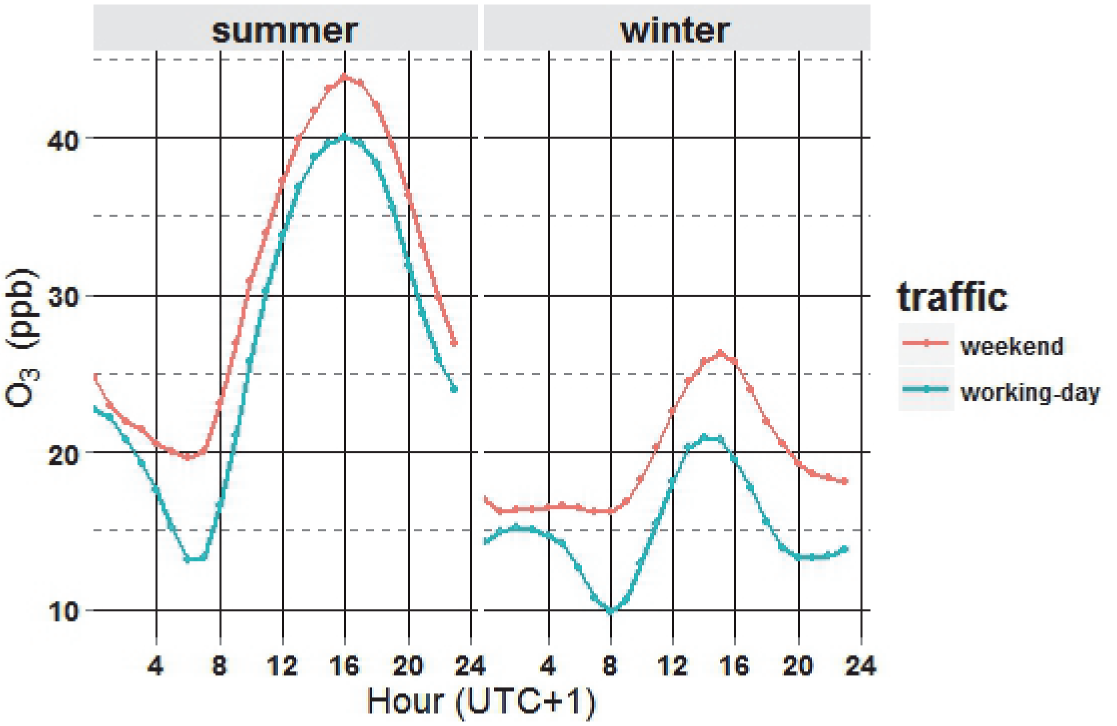

Figure 44 Diurnal course of O_3 during summer and winter half-year as affected by traffic volume over the 2012−2014 period (in ppb).

2.5.5.3 NH_3 measurements at all level II plots over the measuring period 2012−2014

Material and methods

Ammonia (NH_3) air concentrations (at a height of 2.5−3 m, except for Brasschaat) have been measured using Radiello passive samplers since 2009 (Figure 45). Measuring posts were located in a clearing or a pasture adjacent to the plots. The samplers are housed in a shelter attached to the post at a height of 2.2−2.9 meter, except for Brasschaat were measurements were conducted at 24 m height. At Brasschaat, where measurements were also conducted using active sampling methods (combination of annular dry and wet denuders), a longer time-series is available. The cartridge adsorbent of the passive sampler is made of microporous polyethylene material and impregnated with phosphoric acid. Ammonia is adsorbed as ammonium ion. Airborne ammonium salts dispersed as particulate matter do not cross the diffusive membrane of Radiello.

Figure 45 Shelter with NH_3-passive samplers mounted on a tower rail at 24 m height.

Results 2012−2014

Annual average ammonia concentrations are presented in Table 14. During 2013, the measuring post at Gontrode was vandalized and no annual average could be calculated. Concentrations at several plots tended to be lower during 2013, probably due to the harsher winter conditions.

The annual pattern of ammonia concentrations is characterized by a strong spring maximum, occurring after manure spreading (Figure 48−Figure 52). In 2013, however, NH_3 spring peak concentrations were less pronounced compared to 2012 and 2014, probably because of the prolonged frost in March, which didn't allow proper manure spreading. During 2012 and 2014, ammonia concentrations during the month March were substantially higher compared to 2012 and amounted to values of ± 8−10 $\mu g\ m^{-3}$ at Wijnendale, Ravels and Gontrode. At the other two plots, ammonia spring maxima were less pronounced due to the absence of animal husbandry in close proximity (< 5 km) of the measuring sites. At Brasschaat, however, it was found that air masses contained more ammonia when winds blew from the eastern sector where concentrated livestock facilities are located in more remote municipalities (Neirynck et al., 2007). Information about ambient ammonia concentrations at the site was also available from previous measuring campaigns. Annual NH_3 concentrations measured above the forest have remained rather constant (around 2.5−3.5 $\mu g\ NH_3\ m^{-3}$). Little information is available about long-term trends in particle ammonium, but separate measurement campaigns suggest that pNH_4 might have declined more rapidly compared to gaseous ammonia. Measurements, using a dry annular denuder combined with filter-packs, carried out by De Temmerman and Overloop (1999), showed that particle ammonium contributed 61% to the total reduced nitrogen concentration (NH_x) in 1997. Its share dropped towards 42% and 37% during measurement campaigns conducted by VITO in 2000/2001 (Neirynck et al., 2007) and CEH over the period 2007−2008 (Flechard et al., 2011), respectively. Also during the latter measurement campaigns, a combination of annular denuder and filter-pack were used to determine total reduced nitrogen concentrations.

Table 14 Annual average ammonia concentrations measured at the 5 level II sites (in $\mu g\ m^{-3}$, ± sd)

Year	**WIJ**	**RAV**	**BRA**	**GON**	**HOE**
2012	6.0 ±2.3	4.9 ±1.5	3.1 ±1.4	3.5 ±2.0	1.3 ±0.9
2013	4.3 ±1.5	3.5 ±1.7	2.5 ±1.4	NA	0.9 ±0.4
2014	5.6 ±2.6	3.7 ±1.6	2.6 ±2.0	5.1 ±2.6	1.2 ±0.9

Although ammonia concentrations are highly dependent on the manure application time window, they are also affected by meteorological conditions such as relative humidity, temperature, wind speed and precipitation. At Brasschaat, where ammonia was measured on a weekly to biweekly time basis, ammonia concentrations were more elevated during conditions of low relative humidity which favour volatilization of applied manure (Figure 46). Also the impact of precipitation was significant as it enhanced (wet and dry) deposition, lowering the ammonia levels in the atmosphere (Figure 47). Pearson correlation coefficients were -0.7 and -0.5, respectively.

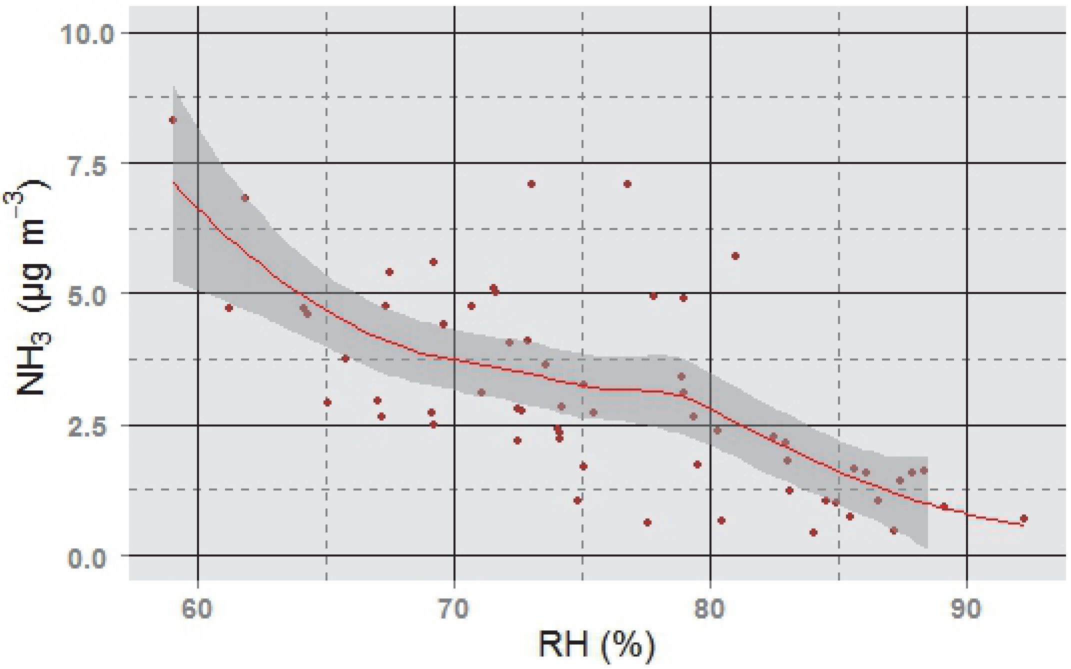

Figure 46 Relationship between biweekly NH_3 concentrations (µg m^{-3}) and relative humidity (%) at Brasschaat (n = 62).

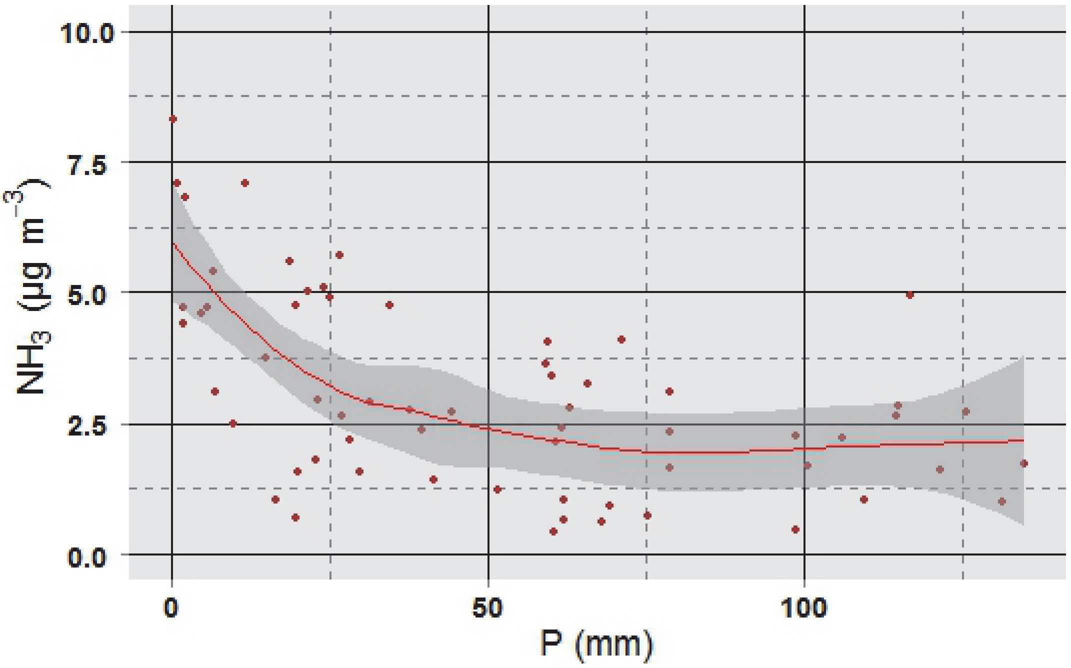

Figure 47 Relationship between biweekly NH_3 concentrations (µg m^{-3}) and precipitation (mm) at Brasschaat (n = 62).

The fertilization effect of NH_3 can in the longer term lead to a variety of adverse effects, including growth stimulation (which can alter species balance with some less-sensitive species being potentially out-competed) and increased susceptibility to abiotic (drought, frost) and biotic stresses.

Annual mean concentrations at every site were therefore compared with the long-term **critical levels (CLe's)** of ammonia recommended in the Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads & Levels and Air Pollution Effects, Risks and Trends (CLRTAP, 2014) (Figure 48−Figure 52). Two different long-term critical levels are currently in use:

> A: The long-term **CLe for lichens and bryophytes**, including ecosystems where lichens and bryophytes are a key part of the ecosystem integrity, of 1 µg m^{-3} (annual mean);
>
> B: The long-term **CLe for higher plants**, including heathland, grassland and forest ground flora and their habitats, of 3 µg m^{-3}, with an uncertainty range of 2-4 µg m^{-3} (annual mean)

A one tailed t-test showed that the lower long-term Cle for lower plants was significantly exceeded at all Level II sites, except at the location in Sonian forest (*p*-value = 0.1297). With regard to higher plants, the long-term Cle of 3 µg m^{-3} was not significantly exceeded at the site in Sonian forest and the measuring tower located in the municipality of Brasschaat (*p*-values resp. 1 and 0.8449).

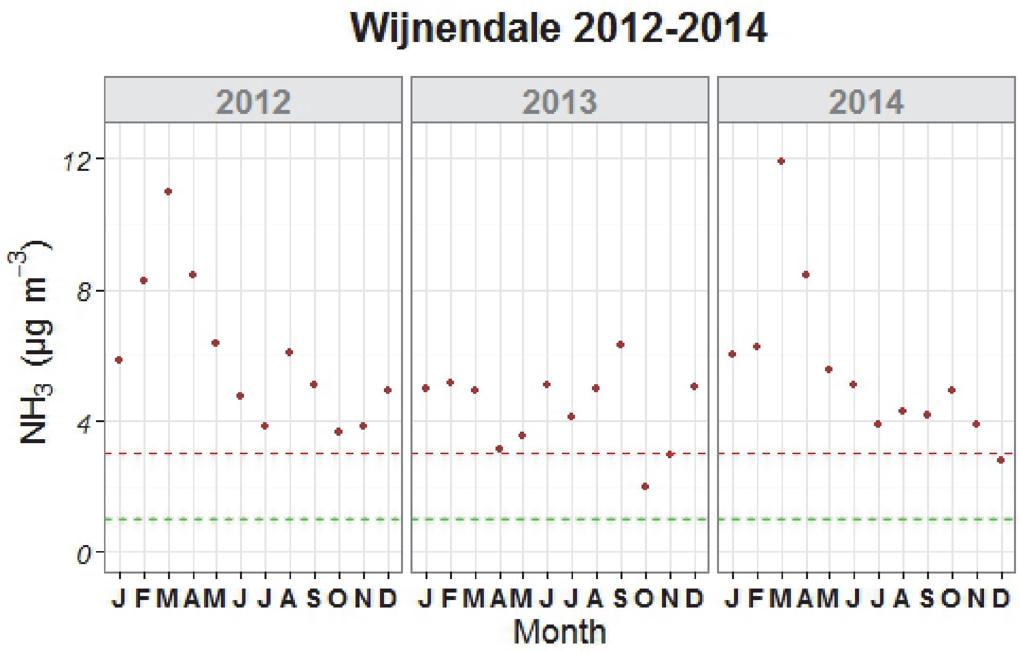

Figure 48 Annual variability in ambient ammonia concentrations during the years 2012, 2013 and 2014 at Wijnendale (in µg m^{-3}). Horizontal lines represent the annual critical level of 1 and 3 µg m^{-3} for lower and higher plants respectively.

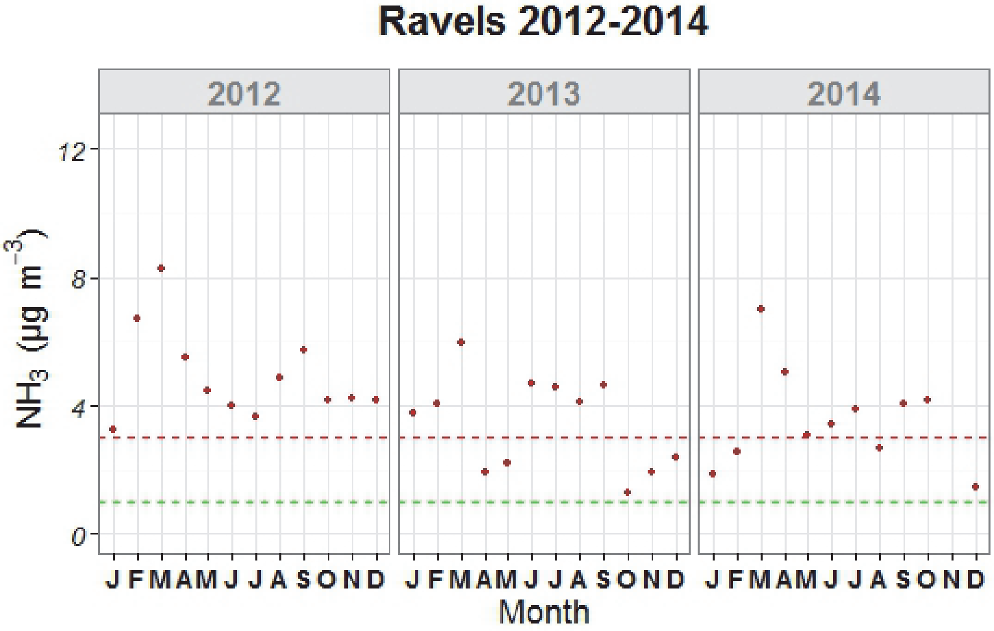

Figure 49 Annual variability in ambient ammonia concentrations during the years 2012, 2013 and 2014 at Ravels (in µg m^{-3}). Horizontal lines represent the annual critical level of 1 and 3 µg m^{-3} for lower and higher plants respectively.

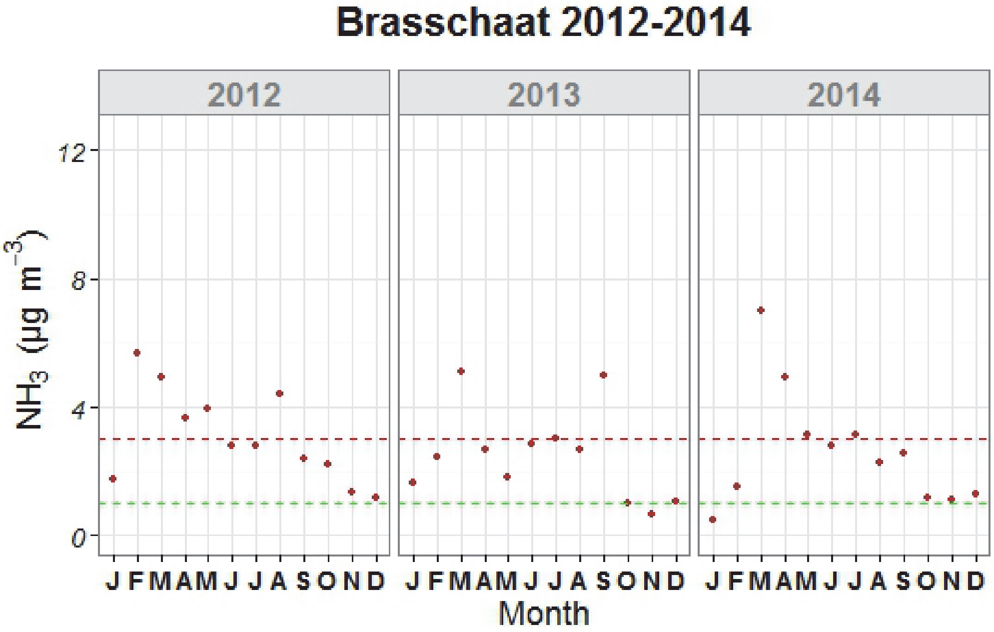

Figure 50 Annual variability in ambient ammonia concentrations during the years 2012, 2013 and 2014 at Brasschaat (in µg m^{-3}). Horizontal lines represent the annual critical level of 1 and 3 µg m^{-3} for lower and higher plants respectively.

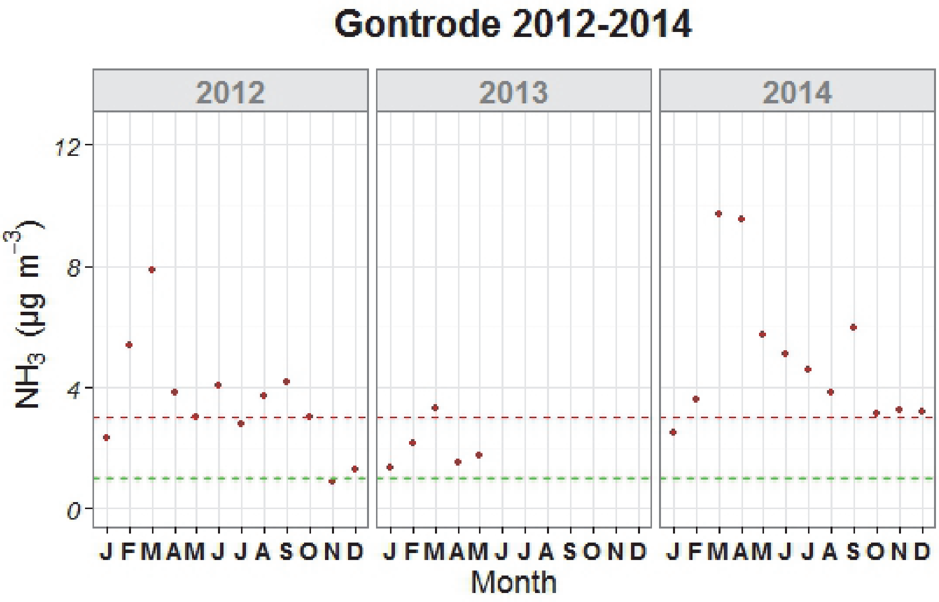

Figure 51 Annual variability in ambient ammonia concentrations during the years 2012, 2013 and 2014 at Gontrode (in µg m^{-3}). Horizontal lines represent the annual critical level of 1 and 3 µg m^{-3} for lower and higher plants respectively.

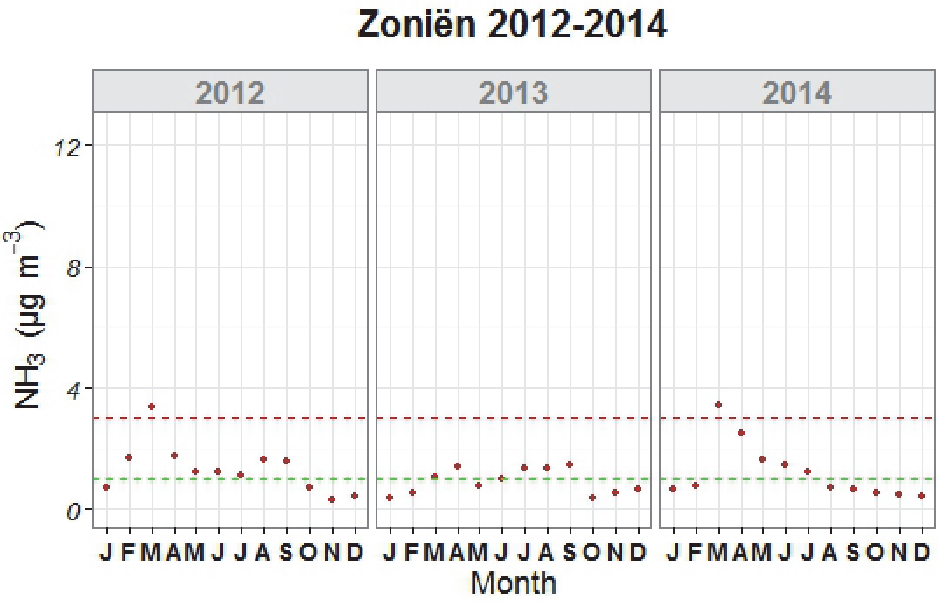

Figure 52 Annual variability in ambient ammonia concentrations during the years 2012, 2013 and 2014 at Sonian Forest (Hoeilaart) (in µg m^{-3}). Horizontal lines represent the annual critical level of 1 and 3 µg m^{-3} for lower and higher plants respectively.

3 Focus on ozone concentrations and fluxes measured at Brasschaat

3.1 Two-decadal trends of ozone in relation to meteorological variables

Ozone concentrations followed increasing trends since the onset of the measurements in 1995 (Figure 53). The level of increase was, however, dependent on the percentile rank. The most marked increase (> 5 ppb decade^{-1}) was noticed in the lower percentile ranges (10th, 30th, 50th percentile). Annual median ozone levels increased by 44% since 1995 and amounted to 45 µg m^{-3} in recent years. In the higher ozone range, no significant trend appeared to exist.

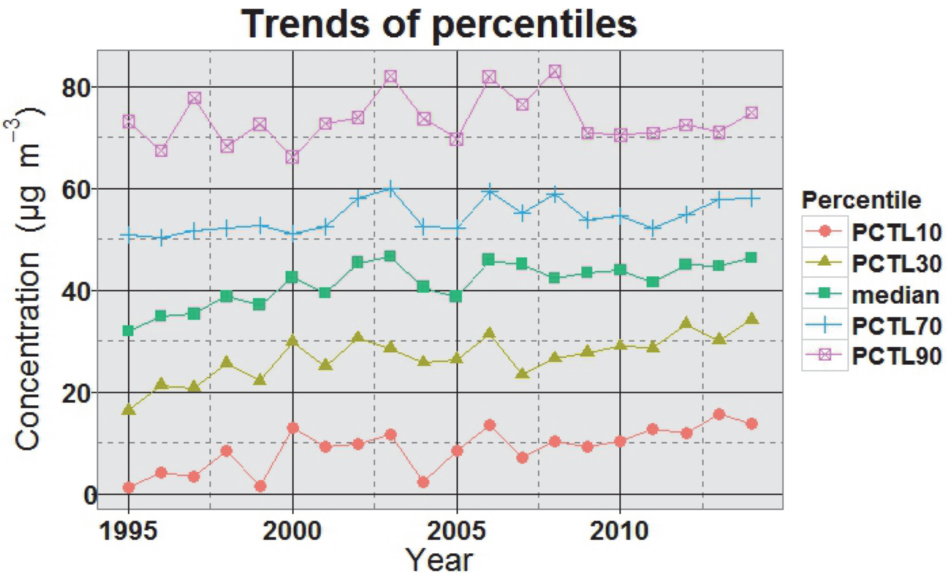

Figure 53 Trends of annual median value along with 10th, 30th, 70th and 90th percentiles over the period 1995−2014 (in µg m^{-3})

The increase in ozone levels was especially marked during the months March and April, which coincides with the springtime tropospheric ozone maximum (Figure 54). During autumn and winter, the increase was also evident but the slope was less steep compared to the spring months. No distinct trend was shown during the summer, except for August where average ozone levels even followed declining trends. The contrasting seasonal trends in ozone levels were further elucidated using a GAMM-model. The model was, in a first step, applied to the dataset with year and day of the year as explanatory variables (deviance explained = 47%). Interactions between both covariates are highly significant (Figure 55).

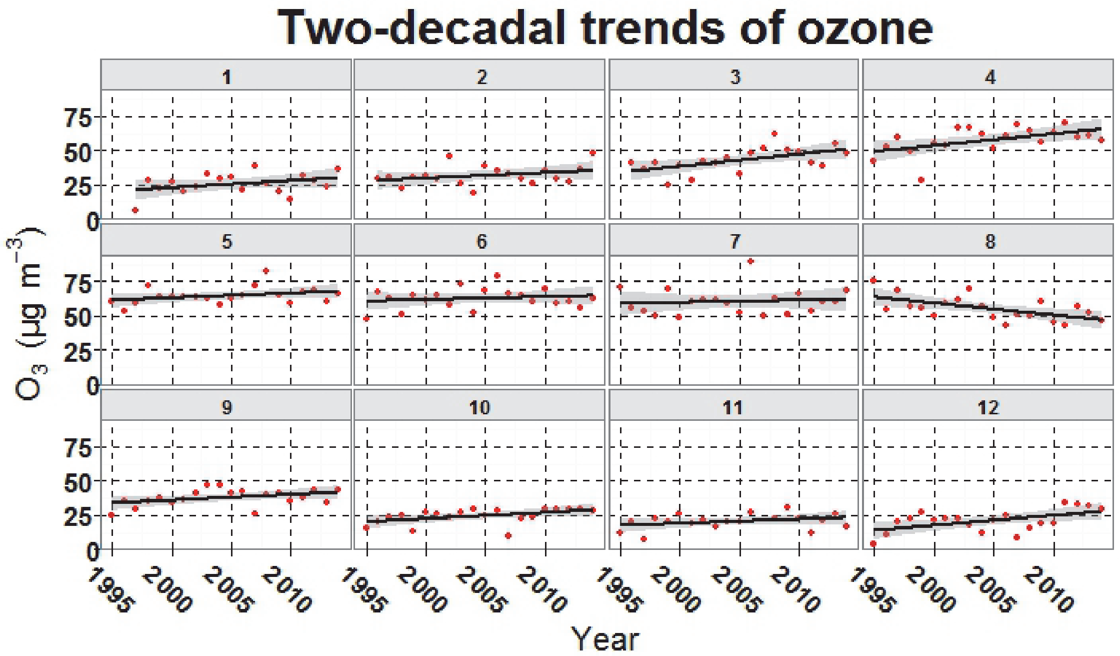

Figure 54 Two-decadal ozone trends for each month. Long-term trends are presented using linear models. Red dots represent the monthly means for a given year (in µg m^{-3}).

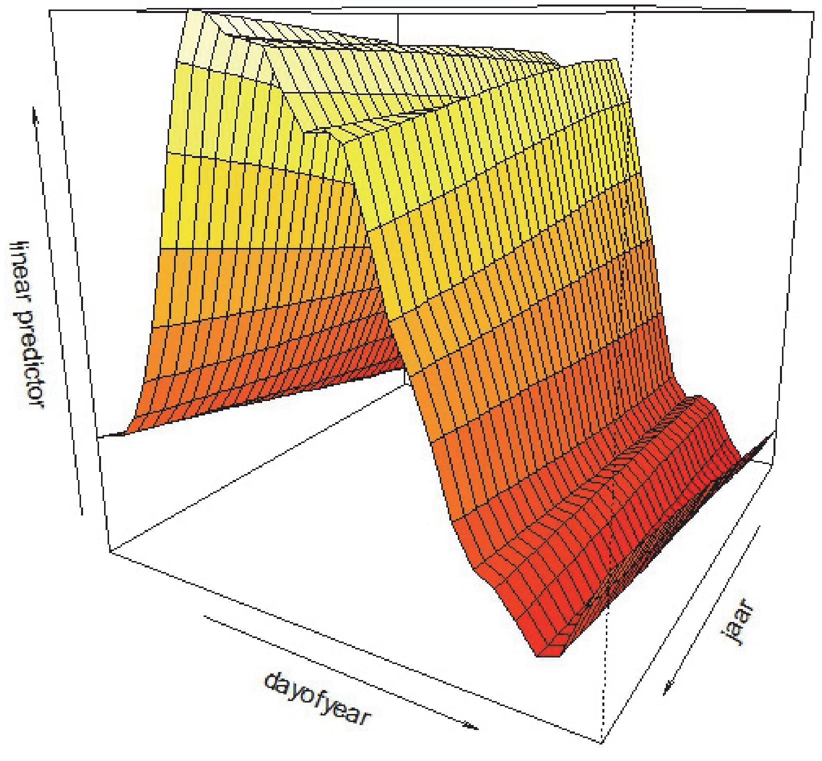

Figure 55 Impact of year and day of year on ozone concentrations over the 2-decade monitoring period.

The GAMM-model was further expanded with NO (its main titrant) and measured meteorological variables as temperature (Tmax), wind speed (WS) and direction (WD), solar radiation (ZON) and air pressure (Pair). Impact of meteorological variables was shown to be highly significant. In case of temperature, a strong non-linear relationship with ozone could be found (Figure 56). When a threshold of 20 degrees Celsius was exceeded, ozone concentration rapidly increased. Solar radiation was linearly correlated with ozone concentrations. The positive impact of wind speed rather indicated an indirect effect as increasing wind speeds lead to a dispersion of NO concentrations, decreasing the titration of ozone (Figure 57). Ozone levels were found to reach the highest levels in the northern wind sector, when NO_x concentrations are negligible. When the influence of meteorology was added to the model, the explained deviance further increased to 82% but it was found that increasing trends, especially during the spring months, still persisted when meteorological and pollution effects were taken into account. According to Monks et al. (2015), the steady increase in ozone mixing ratios may be due to a number of factors such as (a) changes in anthropogenic emissions of precursors (local, regional and global), (b) effects of biomass burning (both regional and global), (c) changes in stratosphere–troposphere exchange, (d) changes in geographical emission patterns, (e) changes in land cover and (f) changes in meteorology (e.g. transport patterns, rain, radiation, temperature).

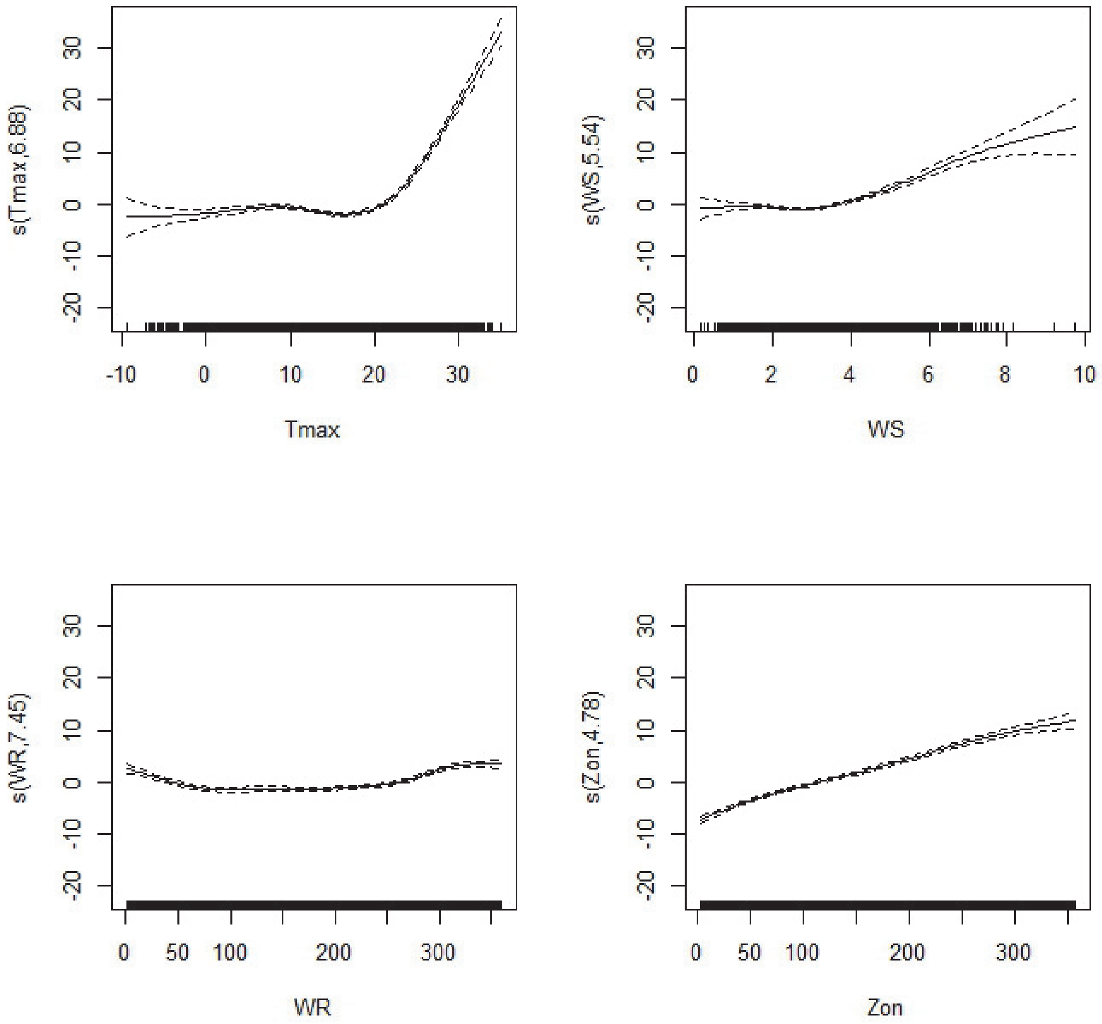

Figure 56 Significant smoothers for non-linear relationships between daily ozone concentrations and meteorological variables maximum temperature (T_{max}, units in degrees celsius, wind speed (WS, units in m s^{-1}), wind direction (WR, units in degrees) and solar radiation (Zon, solar radiation in W m^{-2}) as derived from GAMM-model.

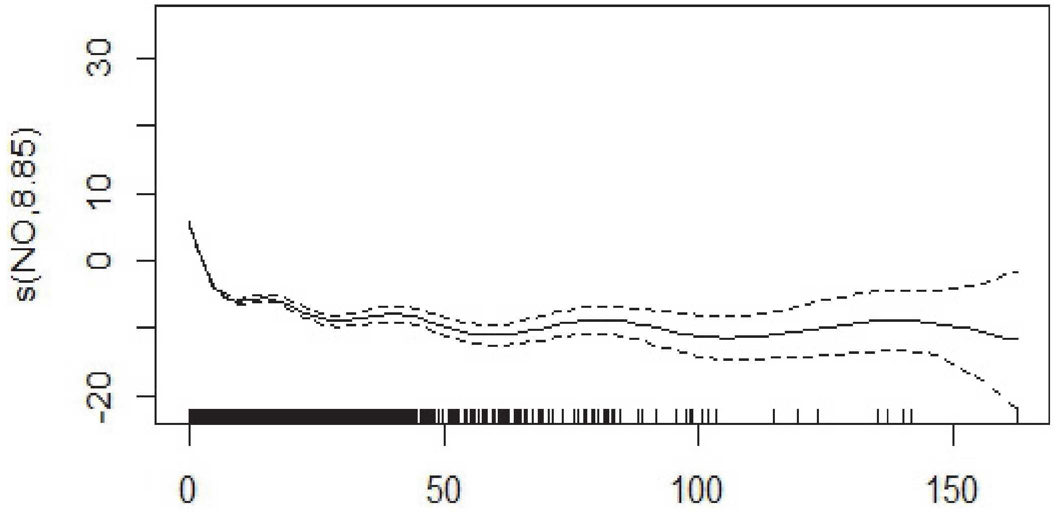

Figure 57 Significant smoother for non-linear relationships between daily ozone concentrations and NO, as derived from GAMM-model.

3.2 Daily course of ozone concentrations and fluxes across the four seasons

3.2.1 Material and methods

Fluxes (F) of ozone were obtained by multiplying the measured ozone gradient from the 24 and 40 m height interval with the turbulent diffusivity, which is calculated from the sonic anemometer measurements (Neirynck et al., 2012). The measured turbulent diffusivity is corrected for stability effects and is, as such, larger during the daytime (higher instability of atmosphere is encountered).

The measured ozone flux (F) was partitioned into a stomatal (Fs) and a non-stomatal part (Fns), using a stomatal conductance model. In order to compute the stomatal ozone flux, the canopy-scale stomatal resistance $R_s(H_2O)$ had to be modelled and adjusted for the diffusivity of ozone. The canopy-scale stomatal resistance $R_s(H_2O)$ was obtained from a leaf physiological submodel, which operates in a process-based multi-layer canopy model leaf physiological submodel, which operates in a process-based multi-layer canopy model.

3.2.2 Results

The long-term average O_3 flux (F) was -366 ng m^{-2} s^{-1} for the period 2000−2010 (Neirynck et al., 2012). Highest deposition fluxes were measured during spring and summer. Long-term average daytime and nighttime fluxes during the summer half-year (defined as the period spanning DOY 61–243) amounted to -0.60 and -0.20 µg m^{-2} s^{-1}, respectively. Ozone fluxes peaked at noon (Figure 59), whereas O_3 concentrations rather displayed maxima in the afternoon (Figure 58). Deposition fluxes of ozone are not only ruled by ozone concentrations but also environmental variables such as the friction velocity (mechanically generated turbulence), solar radiation (convection) and the stomatal conductance (which is controlled by photosynthetically active radiation, vapour pressure deficit, soil water availability and temperature) affect the diurnal variability of the ozone uptake. Ozone concentrations are mainly temperature driven.

Also during the winter half-year a substantial O_3 deposition was measured. During autumn and winter, average daytime fluxes were -0.40 and -0.27 µg m^{-2} s^{-1} , respectively. Also nighttime deposition occurred unexpectedly. Nighttime deposition during autumn and winter averaged -0.18 and -0.16 µg m^{-2} s^{-1} , respectively.

Nighttime uptake of ozone was observed across all the seasons and this was somehow unexpected. This could be related to chemical gas phase reactions with monoterpenes released from resin canals during the night or nitric oxides emitted from the forest floor as a consequence of biogenic processes (Pilegaard et al., 2006). Since these processes are generally temperature driven, they become increasingly important during the daytime. It was also shown that partial stomatal closure occasionally occurred at nighttime during the growing season, especially during rainy summers (high soil water availability). This could also explain some part of the nighttime ozone uptake during the summer half-year.

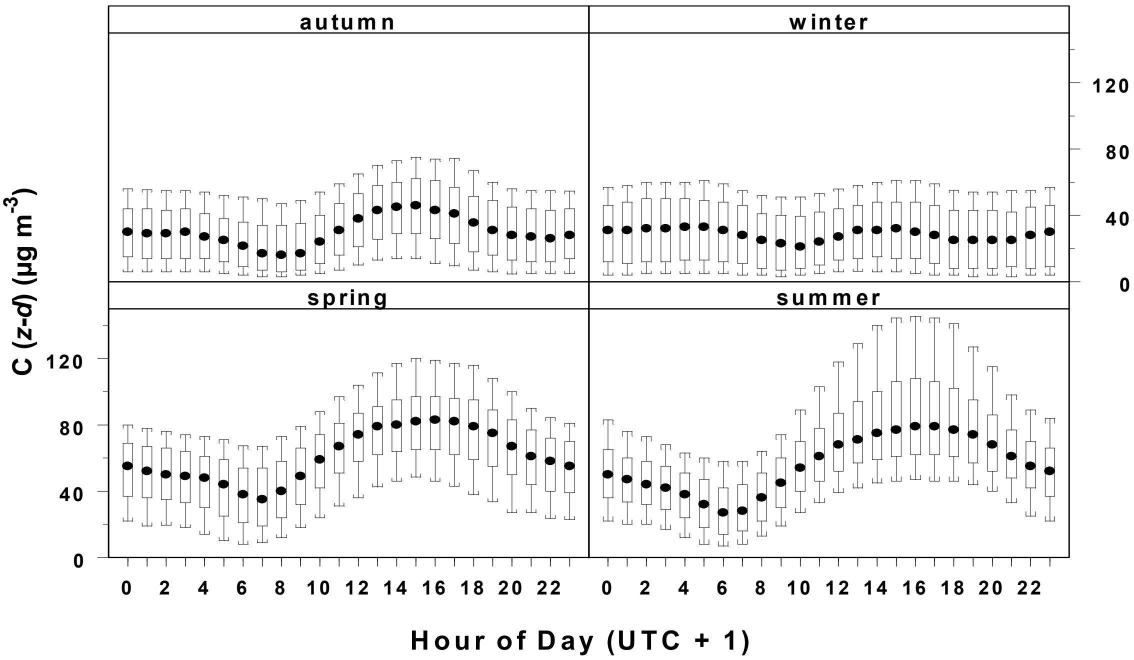

Figure 58 Diurnal variability in hourly ozone concentrations in all seasons at the geometric mean of the ozone gradient averaged over the period 2000–2010. Truncated boxplots with median and lower/upper quartiles are shown. Whiskers are drawn to the 10th and 90th percentiles.

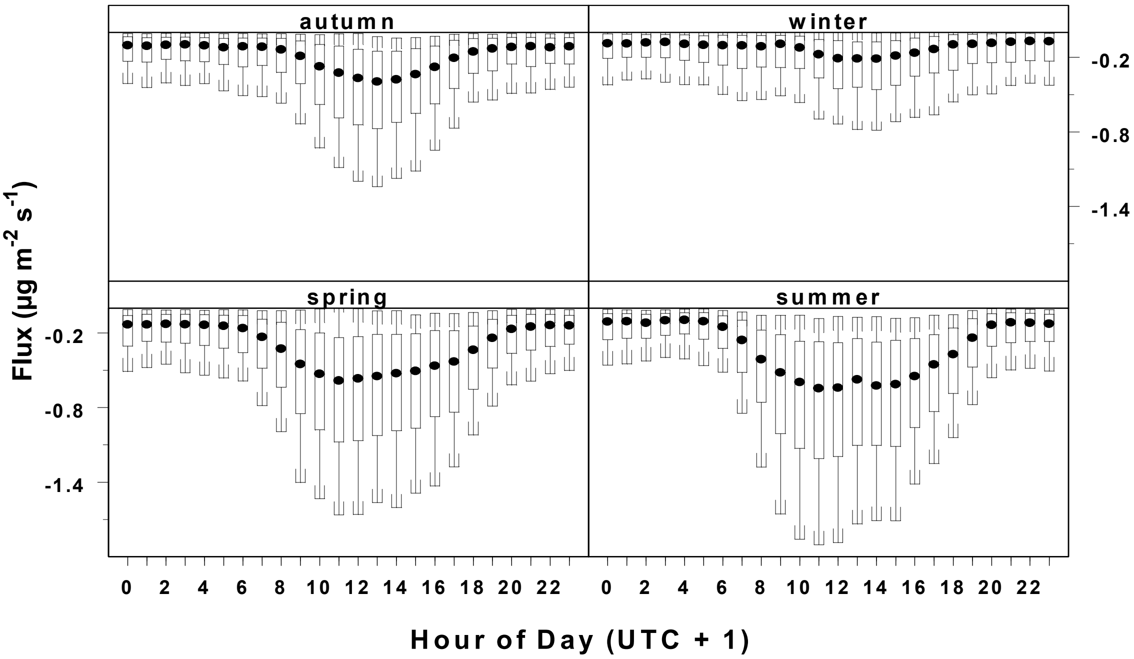

Figure 59 Diurnal variability in hourly ozone fluxes in all seasons averaged over the period 2000–2010. Truncated boxplots with median and lower/upper quartiles are shown. Whiskers are drawn to the 10th and 90th percentiles. Fluxes are presented as negative values.

In contrast to expectations, ozone deposition was mainly driven by non-stomatal processes. The fraction of the daily stomatal fluxes to the daily measured fluxes (Fs/F) averaged about 20% (Figure 60). The latter fraction was, however, subjected to a high seasonal and diurnal variability. Highest Fs/F fractions were measured during the summer (28%) and spring (20%), with ratios peaking in the afternoon (38% and 30% respectively). During autumn and winter the Fs/F ratio decreased to 12% and 8% respectively. Lowest Fs/F ratios were reached in the morning hours.

Highest non-stomatal deposition was measured during the growing season, which might be due to higher O_3 levels and more intense cuticle or gas-phase reactions with biogenic volatile organic compounds (BVOC) or nitrogen monoxide (NO). The emission of monoterpenes, like α-pinenes, β-pinenes and 3-carenes, typical for pine trees and coniferous forest in general, is temperature-dependent and globally peaks in the summer half-year (Goldstein et al., 2004, Holzke et al., 2006; Janson, 1993). Oxidation products of these reactive terpenes were measured during a summer campaign at our site (Gomez-Gonzalez et al., 2012), which indicated that ozonolysis of terpenes could have been important.

The presence of NO-emission at our nitrogen saturated site was evidenced by upward NOx-fluxes (Neirynck et al., 2007), which annually averages between 0.010-0.030 ppb m s^{-1}. Also gas flux measurements from incubated soil and forest floor samples indicated the presence of NO emission (Wagner, 2009). Nitric oxide was found to be emitted from forest floor samples at rate of ± 300 µg N m^{-2} h^{-1} (at ambient moisture content). Emission of NO is claimed to be important at coniferous sites, especially those which are nitrogen saturated (Pilegaard et al., 2006). Also the advanced acidification state of the site could have exacerbated NO losses during chemical processes (Venterea et al., 2004).

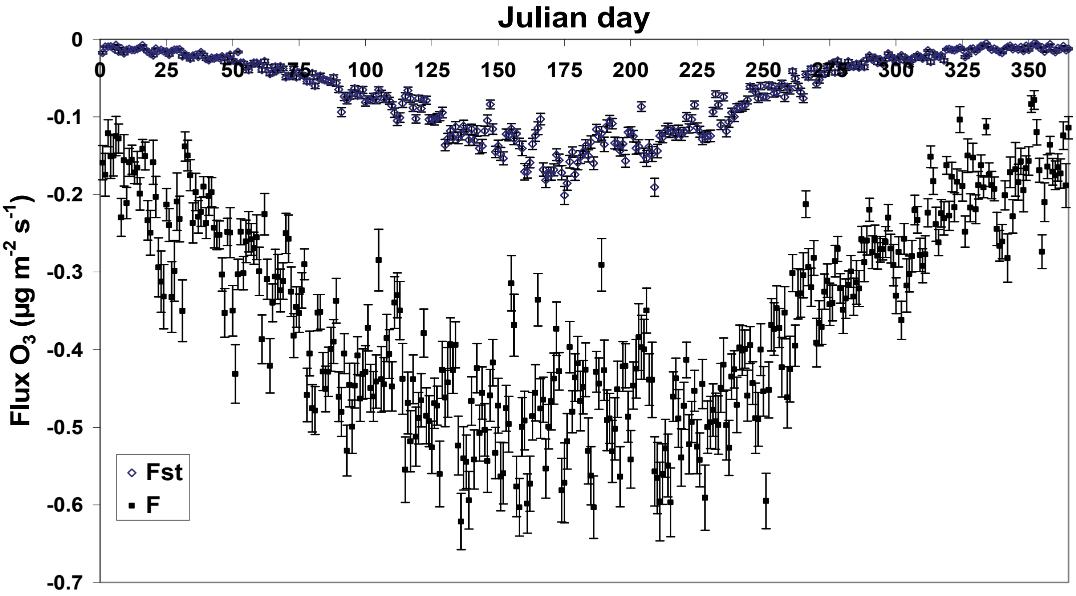

Figure 60 Diurnal variability in the daily ratio of stomatal flux (Fs) to measured flux (F) averaged over the 2000-2010 period. Standard errors around the mean are shown by the small vertical bars (n = 550).

3.3 Critical levels of ozone (AOT40 versus POD)

3.3.1 Exposure- and flux- based indices for ozone risk assessment

For ozone, both cumulative concentration-based as cumulative stomatal flux-based critical levels are described for forest trees. These indices are compared with their critical levels to judge the hazard for ozone damage.

The exposure-based index AOT40 (in ppb*h or ppm*h) is the sum of the difference between the hourly mean ozone concentration at the displacement height (d + z0) and the threshold of 40 ppb for all daylight hours accumulated over the period April till September. For forests, a critical level of 5000 ppb hrs involving a growth reduction of 5% is used.

In contrast to concentration based indices, flux based indices provide an estimate of the amount of ozone entering through the stomata and reaching the sites of action inside the plant. The accumulated Phytotoxic Ozone Dose (i.e. the accumulated stomatal flux) of O_3 above a threshold of Y (PODY) is calculated for the period April–September as the sum of the differences between hourly mean values of Fs and Y nmol m^{-2} s^{-1} when Fs exceeds the threshold Y (during daylight hours). The latter is set to 1 nmol m^{-2} s^{-1} (CLRTAP, 2014). The stomatal flux-based critical level of ozone, CLef mmol m^{-2} PLA (projected leaf area), is then the cumulative stomatal flux of ozone, PODY, above which direct adverse effects may occur according to present knowledge. Values of CLef are species-specific and have been identified for the forest trees birch, beech and Norway spruce. For Scots pine no specific critical has been proposed, to our knowledge. We adopted a stomatal flux critical level value (Clef) of 8 mmol m^{-2} PLA from Norway spruce (2% reduction in biomass), based on dose-effect relationships by Karlsson et al. (2007).

3.3.2 Two-decadal trends of the ozone indices

The AOT40-index exhibited maxima during the years 1995, 2003 and 2006 (resp. 15.0, 16.3 and 16.7 ppm hrs) (Figure 61). The critical level of 5000 ppb hrs was exceeded over the entire period. The concentration-based index is, however, following decreasing trends during recent years. The hourly threshold of 200 µg m^{-3}, implemented by the UNECE (Council Directive 92/72/EEC) for protection of vegetation, was less frequently exceeded. The daily threshold value of 65 µg m^{-3} was more frequently exceeded during recent years, probably because of the increasing background concentrations.

The annual values of POD1 between 2000 and 2010 ranged between 14 and 22 mmol m^{-2}, which largely exceeded the critical level of 8 mmol m^{-2}, adopted from Norway spruce (implying a 2% reduction in biomass).

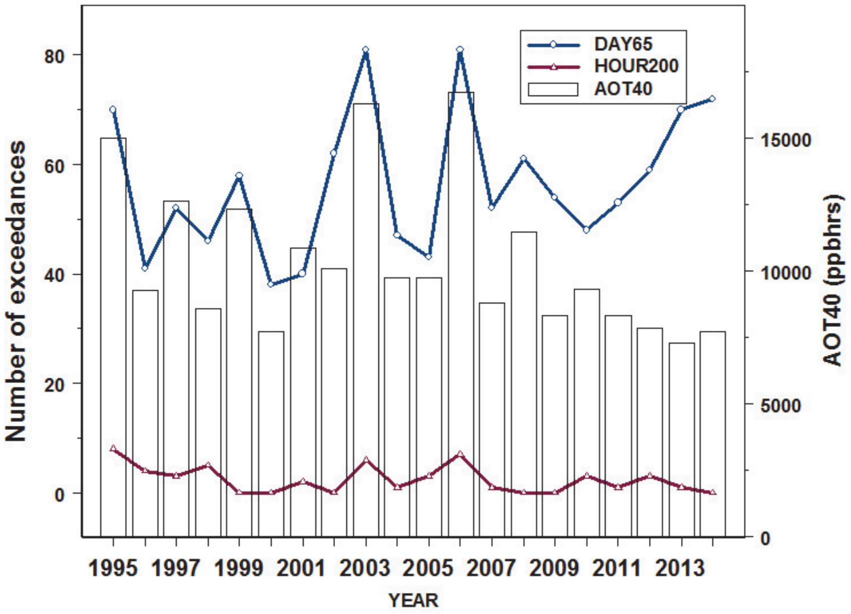

Figure 61 Two-decadal trends of concentration based ozone indices; accumulated ozone exposure over a threshold of 40 ppb and number of exceedances of the daily critical threshold value of 65 µg m^{-3} and hourly critical level of 200 µg m^{-3} adopted for protection of vegetation.

4 Level I plots Flanders: Forest condition monitoring using a systematic grid

4.1 Introduction

INBO coordinates a yearly assessment of the forest health status in the Northern region of Belgium. This large scale forest condition survey in international terms is called the Level I-survey. Forest health monitoring started in Flanders in 1987. The survey was set up by international cooperation programmes of the United Nations (UNECE, CLRTAP, www.icp-forests.net) and the EU (EC Regulation 3528/86, Forest Focus Regulation, Life+ FutMon programme). Crown condition assessments are executed following the ICP Forests Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests (ICP Forests, 2010).

The forest condition survey aims at a general description of the forest condition in Flanders and more specific for some important tree species. The changes in crown condition are considered and, if possible, explained. The survey results are published in reports and submitted to the database of ICP Forests. ICP Forests is responsible for the reporting at the Pan-European level to the Working Group on Effects of the Convention on Long-Range Transboundary Air Pollution through the international Forest Condition reports (Technical Report, Executive Report) and to ForestEurope which is the Ministerial Conference on the Protection of Forests in Europe.

Figure 62 Crown condition assessment in a Level I plot with *Q. robur*.

4.2 Plots and trees

The European crown condition survey (Level I) is developed by means of a systematic grid of 16 by 16 km. In Flanders, the monitoring was originally conducted on an 8 x 8 km grid, with 41 monitoring plots. The Level I plots were selected both in private forests as in public forests.

Originally 10 plots were part of the international 16 x 16 km Level I survey. From 1995 on the Level I survey was performed on a 4 x 4 km grid, with 72 regional plots (Figure 2). Nowadays data from 8 international plots is yearly reported to ICP Forests, together with results from the regional survey.

In 1987 the area of the Level I plots was not defined. In each plot a cross-cluster sampling was used to select 4 groups with 6 trees. The number of trees was exactly the same in every plot. At this moment the ICP Forests manual states that Level I plots should have a defined dimension and shape. Many countries changed their sampling design. In 2009 circular plots were installed and from 2012 on, sample trees have been selected only in these circles. The radius of the circular plots is 18 m and the area of the plots is 1018 m².

In 2014, 71 plots were visited and 1661 trees were assessed (Table 15). The most common tree species in the inventory are European oak (*Quercus robur* L.), Scots pine (*Pinus sylvestris* L.), Common beech (*Fagus sylvatica* L.), Northern red oak (*Quercus rubra* L.), Corsican black pine (*Pinus nigra* subsp. *Laricio* var. *Corsicana* Loud.) and poplar cultivars (*Populus sp.*). There is a high number of Black alder trees (*Alnus glutinosa* (L.) Gaertn.), but this sample is almost completely selected in one plot.

Table 15 Tree species and number of sample trees in Level I (Belgium/Flanders).

Species		**n**	**%**
Quercus robur		389	23.4
Fagus sylvatica		118	7.1
Quercus rubra		93	5.6
Populus sp.		60	3.6
Other broadleaves	*Alnus glutinosa*	76	4.5
	Castanea sativa	49	3.0
	Quercus petraea	44	2.6
	Fraxinus excelsior	35	2.1
	Acer pseudoplatanus	21	1.3
	Betula pendula	20	1.2
	Robinia pseudoacacia	9	0.5
	Populus canescens	3	0.2
	Carpinus betulus	2	0.1
	Prunus avium	1	0.1
	Betula pubescens	1	0.1
	Ulmus minor	1	0.1
Other broadleaves (total)		262	15.8
Broadleaves		922	55.5
Pinus sylvestris		556	33.5
Pinus nigra		171	10.3
Other conifers	*Larix kaempferi*	10	0.5
	Picea abies	1	0.1
	Pseudotsuga menziesii	1	0.1
Other conifers (total)		12	0.7
Conifers		739	44.5
Total		1661	100.0

4.3 Crown condition assessment / defoliation

Defoliation is the main criterion used to assess the condition of the crowns. Leaf loss or defoliation is assessed following the ICP Forests Manual Part IV (ICP Forests, 2010). Defoliation is defined as needle or leaf loss in the assessable crown as compared to a reference tree (a healthy reference). Defoliation is observed regardless of the cause of foliage loss (i.e. for example it includes damage by insects).

During the summer months the defoliation of the sample trees is assessed and damage symptoms are described. The observers assess defoliation in steps of 5% using binoculars. Afterwards, the trees are classified in defoliation classes (Table 16). A healthy tree is a tree with a maximum of 10% defoliation. Slightly defoliated trees show less than 25% defoliation but more than 10%.

Trees with more than 25% defoliation are rated as damaged. A distinction is made between moderately and severely defoliated trees. Trees with 100% defoliation are considered as dead.

Attention is paid to a large set of possible damage symptoms on leaves, branches, stem and collar. The extent of the damage is assessed and if possible, the cause of the symptom is reported. Abnormal discolouration means that more than 10% of the crown shows discolouration. Other possible symptoms are partially or totally devoured leaves, dead branches and dead twigs, wounds, deformations, signs of insects or fungi, … In this publication only results of the crown assessment concerning defoliation are reported.

Table 16 Defoliation classes.

class	leaf/needle loss (%)	defoliation
0	0-10	none
1	11-25	slight
2	26-60	moderate
3	61-99	severe
4	100	dead
2-4	26-100	moderate-dead (damaged)

4.4 Results

4.4.1 Results of the survey in 2014

The fieldwork was conducted from July to mid-September. 21.1% of the sample trees showed more than 25% defoliation (Table 17). The overall average defoliation was 23.4%. Severe defoliation was observed on 1.6% of the trees. There was a high mortality rate (1.2%) due to 14 dead trees in one plot. In this plot dieback of *Alnus glutinosa* was caused by *Phytophthora alni* and very wet site conditions. 9% of the trees were in defoliation class 0 and 69.9% in defoliation class 1. The condition of conifers was better compared to broadleaves. 27.3% of the broadleaved trees and 13.3% of the conifers were in defoliation classes 2-4. The mean defoliation was 25.3% in broadleaves and 21.1% in conifers.

Q. robur, *Populus sp.*, *P. nigra* and the trees in the category 'other broadleaves' showed the worst crown condition. The share of damaged trees was 32.4% in *Q. robur*, 21.7% in *Populus sp*. and 35.5% in the 'other broadleaves'. The most affected coniferous species was *P. nigra* with 26.9% of the trees showing more than 25% defoliation. *P. sylvestris*, *Q. rubra* and *Fagus sylvatica* revealed a better condition compared to the other species, with 9.2%, 7.5% and 11% of the trees being damaged.

Fallen and broken trees were detected in several plots and 0.5% of the sample trees were removed for this reason.

Table 17 Share of trees in defoliation classes in 2014.

	class 0 (%)	class 1 (%)	class 2 (%)	class 3 (%)	class 4 (%)	class 2-4 (%)
Total	9.0	69.9	18.3	1.6	1.2	21.1
Broadleaves	11.9	60.8	22.5	2.7	2.1	27.3
Conifers	5.4	81.3	12.9	0.3	0.1	13.3
Quercus robur	9.0	58.6	30.4	1.0	1.0	32.4
Fagus sylvatica	16.1	72.9	11.0	0.0	0.0	11.0
Quercus rubra	2.2	90.3	7.5	0.0	0.0	7.5
Populus sp.	3.3	75.0	15.1	3.3	3.3	21.7
Other broadleaves	19.8	44.7	23.2	7.3	5.0	35.5
Pinus sylvestris	6.1	84.7	9.0	0.0	0.2	9.2
Pinus nigra	3.5	69.6	25.7	1.2	0.0	26.9
Other conifers	0.0	91.7	8.3	0.0	0.0	8.3

4.4.2 Defoliation in 2012−2014

For this period the common sample trees are considered. The total number of trees in the common sample is 1655. These trees were assessed in 2012, 2013 and 2014. Dead trees from the surveys in 2012 and 2013 are not in the common sample because they were left out of the survey in 2013 and 2014 respectively. In this part and in paragraph *4.4.3* we describe the defoliation of all species together and give a separate description for *Quercus robur*, *Fagus sylvatica* and *Pinus sylvestris*.

Considering all species together, mean defoliation and the share of trees with more than 25% defoliation decreased in 2013 but increased in 2014. The share of trees in defoliation classes 2−4 was 21.9% in 2012, 18.5% in 2013 and 21.0% in 2014 (Figure 63). The mean defoliation changed from 23.2% in 2012 to 22.5% in 2013 and 23.4% in 2014 (Figure 64). The significant decrease in 2013 was followed by a significant increase in defoliation in 2014. For the total period, there were no significant changes.

The share of *Q. robur* trees with more than 25% defoliation is high. In 2012 33.9% of the oak trees showed moderate to severe leaf loss. The percentage of trees in damage classes 2−4 decreased to 29.2% in 2013, but in 2014 again more the 30% of the trees were rated as damaged (32.3%). Mean defoliation was above 25% in 2012 (25.4%) but decreased to 24.1% in 2013 and 24.9% in 2014. Changes in defoliation were significant between 2012 and 2013, but not between 2013−2014 or 2012−2014.

F. sylvatica reveals a better crown condition. Mean defoliation is much lower: 17.3% in 2012, 16.7% in 2013 and 18.9% in 2014. Defoliation in beech was significantly higher in 2014 compared to 2012 and 2013. There were no significant changes between 2012 and 2013. The share of trees considered as being damaged was less than 10% in 2012 and 2013 (7.6% and 5.9% respectively). In 2014 11% of the trees showed more than 25% defoliation.

The crown condition of *Pinus sylvestris* improved in 2013. Mean defoliation decreased from 20.5% to 20.0% and the share of trees with moderate to severe needle loss improved from 13.3% to 8.1%. This decrease was statistically significant. In 2014 there was a non-significant increase in defoliation. Mean defoliation in 2014 was 20.2% and 9.2% of the trees were considered as damaged.

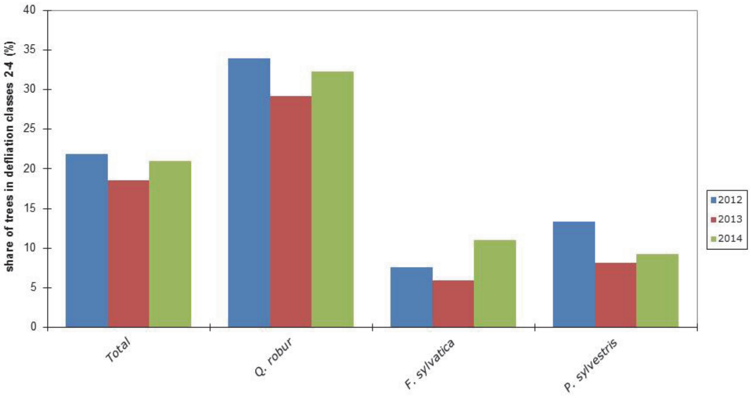

Figure 63 Share of trees in defoliation classes 2−4 in 2012−2014 (common sample trees: total sample, *Q. robur*, *F. sylvatica* and *P. sylvestris*).

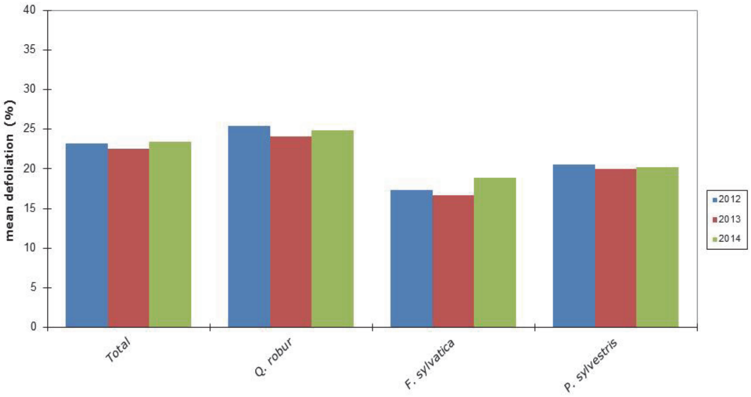

Figure 64 Mean defoliation of *P. sylvestris*, *F. sylvatica*, *Q. robur* and total sample in 2012−2014 (common sample trees).

4.4.3 Trend of the last 20 years of crown condition assessment (1995−2014)

In 1995, 1728 trees were assessed on a total of 72 plots. Because of the changed sampling design, the number of common trees for the whole period is very small. Figure 65−Figure 68 are based on the total sample from year to year.

In Figure 65−Figure 68, mean defoliation and the share of trees in defoliation classes 2−4 are plotted against year of assessment. Mean defoliation (blue line) shows smaller changes from year to year compared to the percentage of trees showing more than 25% defoliation (red line).

The mean defoliation of all species together shows a slight decrease between 1995 and 2008 (Figure 65). Especially the share of trees in damage classes 2−4 is much higher in 1995 in comparison to 2008. After 2008 there is a strong increase, both in mean defoliation and the share of moderately to severely damaged trees. The deterioration in crown condition continues till 2012. In 2013 and 2014 crown condition is recovering but the mean defoliation remains high (23.4%).

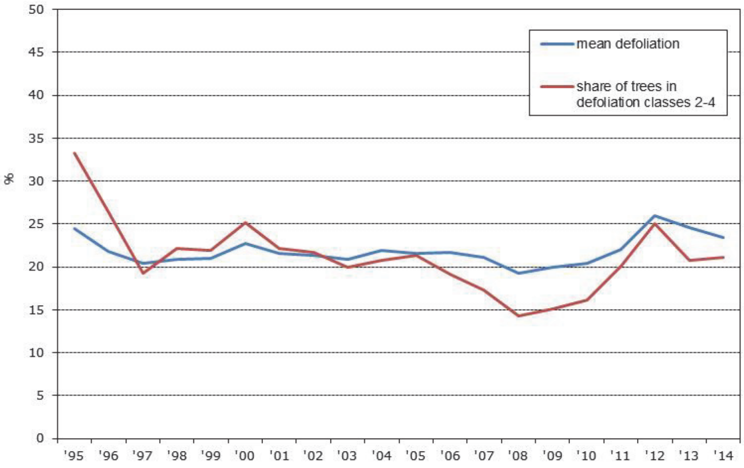

Figure 65 Mean defoliation and share of trees in defoliation classes 2−4 in the period 1995−2014 (total sample).

The condition of *Quercus robur* shows similar trends (Figure 66). From 1995 to 2008 there is a diminishing trend with regard to the share of trees in defoliation classes 2−4. The trend of the mean defoliation is not so clear. From 2009 to 2012 there is an important increase in defoliation. Both mean defoliation and the share of trees considered as damaged are increasing for 4 consecutive years. After 2012 crown condition is improving but the defoliation remains at a high level.

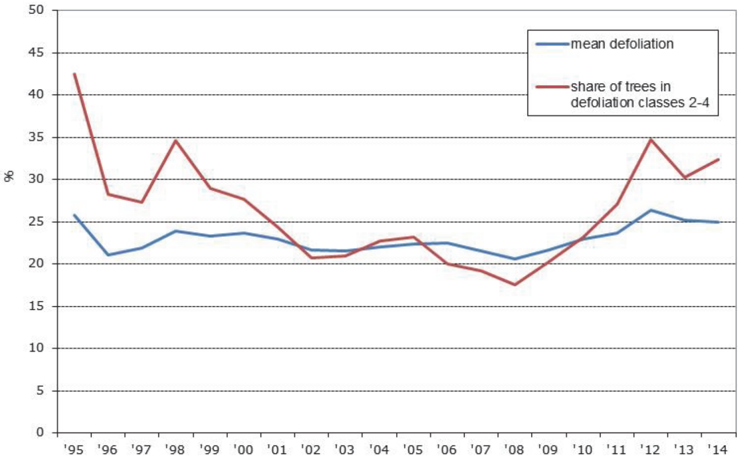

Figure 66 Mean defoliation and share of trees in defoliation classes 2−4 in the period 1995−2014 (*Quercus robur*).

The crown condition of *Fagus sylvatica* is fluctuating. High peaks in defoliation are noticed in 1995 and 2004 but also 2000 and 2011 show a high defoliation in beech (Figure 67). In some years high defoliation scores are correlated with high fructification of the trees (1995, 2000, 2004, 2011). In 2013 and 2014 fructification was observed, but defoliation was not extremely high. There is no trend in defoliation between 1995 and 2014.

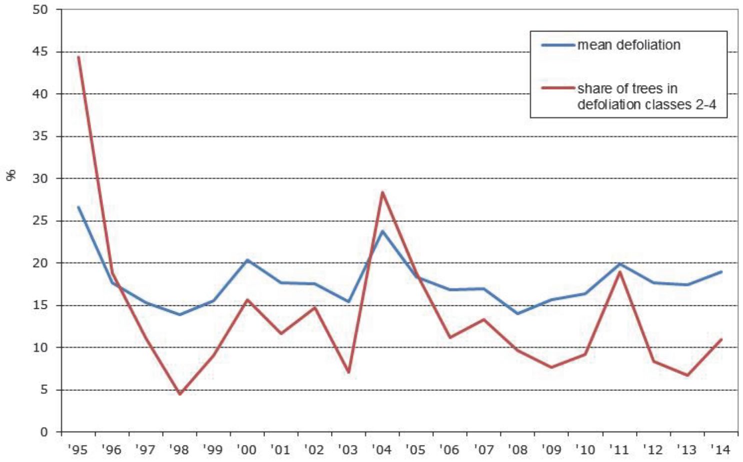

Figure 67 Mean defoliation and share of trees in defoliation classes 2−4 in the period 1995−2014 (*Fagus sylvatica*).

Pinus sylvestris shows a decrease in defoliation (Figure 68). Tree health is improving remarkably from 2000 to 2009. After 2010 there is a short period with an increasing needle loss (2011-2012). Compared to *Pinus nigra* and the total of all species, *P. sylvestris* reveals a good health status.

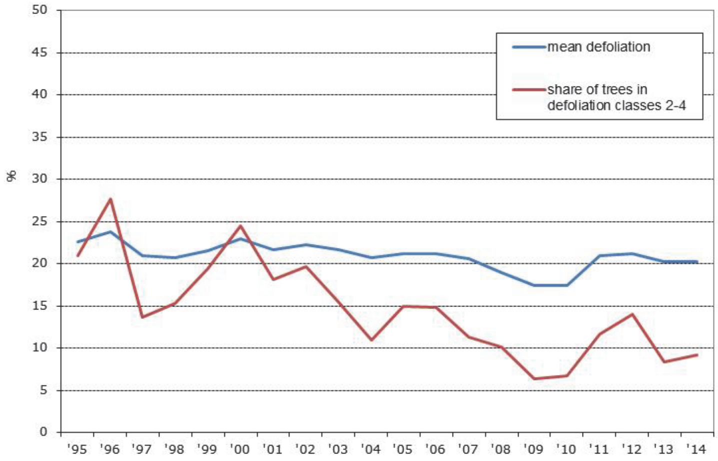

Figure 68 Mean defoliation and share of trees in defoliation classes 2−4 in the period 1995−2014 (*Pinus sylvestris*).

4.5 Conclusion

The results of the Level I survey show that the crown condition of trees in forests is different from one year to another and the health status of the tree species is varying. In Flanders crown condition of *Pinus sylvestris* and *Fagus sylvatica* is better compared to the condition of *Quercus robur*. Many factors are influencing this condition, not only deposition and soil acidification. Site conditions, weather circumstances, insect damage and (fungal) diseases play an important role (e.g. Jactel et al. 2012). At this moment *Q. robur* reveals the weakest condition of these species, because oaks suffer from many threats. This is comparable to the health status of *Q. robur* in other European regions (Michel and Seidling, 2015).

Figure 69 Level I plot in the Campine region of Flanders (plot N° 904, Pijnven forest, *Pinus nigra*).

5 Future and prospects

5.1 Beyond the DPSIR framework

One of the most important challenges of today is to mitigate the impact of the human footprint on the environment. This is vital for humanity as we all heavily rely on natural resources. Natural ecosystems provide various essential ecosystem services such as oxygen, food, energy and clean drinking water. The human impact on ecosystems often leads to a decrease in ecosystem services affecting the living conditions and livelihood of people. A prerequisite for the development of appropriate management measures is, however, an in-depth understanding of ecosystem structures, mechanisms and processes which is one of the core objectives of long-term ecosystem research (Haase, 2016).

To streamline the study on the interplay between the environment and the socio-economic activities, LTER adopted the DPSIR framework to frame its research foci. The DPSIR represents a system analysis view: social and economic developments (i.e. drivers such as demographic growth, technological developments,...) exert pressure (e.g. land use changes, climate change, eutrophication, acidification,...) on the environment and, as a consequence, the state of the environment changes (e.g. loss of biodiversity, loss of sustainability). This leads to impacts on e.g. human health, ecosystems and materials that may elicit a societal response that feeds back on the driving forces (e.g. national emission ceilings,...), on the pressures or on the state of the ecosystems (e.g. forest health condition) or impacts directly, through adaptation or curative action (e.g nature restoration). One shortcoming of the DPSIR framework is however, that it does not necessarily capture the ecosystem changes which may be caused by natural changes and stochasticity but not necessarily by anthropogenic drivers. This is an important reason why long-term ecosystem research is essential when it comes to the detailed analysis of environmental change. There is a need to capture and entangle both, the ecosystem changes driven by natural changes and stochasticity and on the other hand by anthropogenic drivers. Secondly, these changes may occur at different time scales. The reason for setting up LTER-sites and networks has been to address these challenges.

LTER-Belgium aims to create the framework conditions for further integrated and interdisciplinary research which is essential to conduct policy relevant ecological research. The scientific field of ecosystem research comprises three thematic areas, which address complex research issues: process-oriented ecosystem research, biodiversity and nature conservation research and socio-ecological research. This LTER-Belgium report showed a first example of the process-oriented part of the ecosystem research. Other examples are yet to follow. Socio-ecological research in Belgium is however still mostly restricted to project-based research projects, though providing the basis to elaborate on it for the future.

5.2 The Flemish forest condition monitoring network

As the forest condition monitoring programme is running now for more than 25 years, long-term data sets on the different compartments of the forest ecosystem are available. This allows for integrated studies across the different ecosystem components, linking trends in pressures on and status of the forest ecosystem (e.g. the fluxes in deposition and soil solution in Chapter 2). Based on the Level II research, the trends of dissolved organic nitrogen (DON) in deposition and soil solution (2005–2014) are now being evaluated against several indicators for the N status of forests, using several soil solution based element ratios and foliage status indicators (e.g. N:P ratio). Further in-depth evaluations concern the drivers of dissolved organic carbon (DOC) and DON in soil solution. The analysis of repeated solid soil surveys (1989, 1992, 2004, 2014) will examine if trends in the composition of the soil solution match with the chemical analyses of the solid soil.

As the trends detected in the forest health and vitality on the Level II (Chapter 2) and Level I plots (Chapter 4) do not follow exactly the same pattern, further research on the drivers will help us to disentangle the anthropogenic and natural causes.

Future research on the Level II plots will focus on the implications of climate change, eutrophication and acidification recovery for forest ecosystem status and health. While the impacts of climate change will likely increase, it is expected that the currently monotonic (linear) deposition trends will flatten, because it will become increasingly difficult to further reduce the acidifying and eutrophicating emissions. Particularly, we would like to evaluate to what extent the changing environmental conditions will result in either adaptation or resilience and biotic recovery (response of vegetation, ectomycorrhizal fungi, …).

5.3 Synergies within the LTER-Belgium network

Eight Walloon sites of the LTER-Belgium network (number 19 till 26 –see Table 1) are also part of the ICP Forests Level II network, monitoring the same forest ecosystem parameters according to the same or comparable methods. Monitoring results are reported annually to the Programme Coordinating Centre at the European level but untill now the results from the two Belgian regions have not been put together. LTER-Belgium offers a framework to perform joint analyses at the national level to check whether the observed trends are consistent or not, and to explain why. One project where Walloon and Flemish Level II data are already combined is in the calibration of models of forest ecosystem functioning and in simulation studies in the framework of the ECORISK project (http://www.belspo.be/belspo/ssd/science/projects/ECORISK.E.pdf). For this project, data from Brasschaat are currently used to calibrate a nutrient cycling module developed by UCL and coupled with the ANAFORE model.

In the early 1990s, the intensive monitoring plots were selected in order to represent the more important forest species and growing conditions in each country. The forest management in the plot had to be the same compared to the surrounding forest. In general, the Level II sites were installed in forest stand under regular management. A self-evident level of integration of research results would be with the monitoring network of forest reserves in Flanders, which is focusing on the biotic component of the forest ecosystem. The fact that a number of these sites are co-located in the same LTER-sites is a first step towards this integrated evaluation work. Bringing the long term monitoring and research results together will help us to disentangle the natural and the anthropogenic drivers of ecosystem changes.

A further objective is the inclusion of non-forest ecosystem in the study of the biogeochemical cycles. The study of these cycles is currently restricted to the forest ecosystems in Belgium. The need to increase our knowledge on biogeochemistry in ecosystems such as heathlands and grasslands is high and LTER offers the framework to elaborate experience, methods and monitoring techniques across sites. Compiling the current research results at national level can be a first step to define the gaps.

5.4 At the international level

As 13 of the 33 LTER-Belgium sites are closely connected to the UNECE **ICP Forests** programme under the Convention on Long Range Transboundary Air Pollution, future perspectives of the long-term monitoring and research will be related to the developments in this international programmes. While the programme was set up in the 1980s to assess the effects of acid rain on forest dieback, its mission has broadened to provide scientific knowledge on the effects of air pollution in general, climate change and other stressors on forest ecosystems. The major air pollutants are no longer restricted to sulphur and nitrogen oxides, but also concern ozone, volatile organic compounds, persistent organic pollutants, heavy metals, particulate matter, including black carbon and ammonia. ICP Forests aims at providing a continuing overview on forest health, vitality, forest soil condition and biodiversity status in relation to a wide range of anthropogenic and natural stressors. Its central database aims to serve as a reference for global assessments. Furthermore ICP Forests will enhance its cooperation with the other five ICPs (ICP Waters, ICP Mapping and Modelling, ICP Vegetation, ICP Integrated Monitoring and ICP Materials) to promote integrated and cross-sectorial evaluations and reporting as well as unified measurements. The long-term monitoring forms an important part of this work. Though, the work is also underpinned by scientific research on dose-response, critical loads and levels and damage evaluation.

Up to date, data from the Flemish Level II core plots have been involved in numerous international data evaluations. Examples are the data evaluation on DOC trends coordinated by the Expert Panel on Soil and Soil Solution of ICP Forests (Camino-Serrano et al., under review). Data from Flemish Level I plots are currently involved in a data-evaluation on the effect of meteorological variables on the masting pattern and frequency of Quercus robur, Fagus sylvatica and Pinus nigra, coordinated by the Swiss Federal Research Institute (WSL) and ICP Forests. Furthermore there is the European wide study on soil solution based indicators for forest soil acidity. Data from Brasschaat will be involved in an eLTER H2020 project (eLTER WP9 Task JRA 2.1 and 2.3). In 2014, root tips were sampled in Wijnendale, Brasschaat and Hoeilaart in order to determine the species composition of ectomycorrhizal fungi in these plots, as part of a European project coordinated by Kew Gardens, London, UK. Data from the five Level II core plots will also be involved in the ECLAIRE project on forest growth, and in the Seed-C project, both coordinated by the Swiss Federal Research Institute (WSL) and ICP Forests.

A second network at the European level where six of the LTER-Belgium sites are involved is the '**Integrated Carbon Observation System**', the ICOS network (http://www.icos-belgium.be/. It concerns five terrestrial ecosytems sites.

Three of these sites are located in forests equipped with a flux tower (Brasschaat, Vielsalm and Robinette). One emerging ICOS site is being set up in the National Park De Hoge Kempen in a dry heathland-grassland vegetation. This site will be equipped with an ECOTRON+ installation as part of the AnaEE ESFRI infrastructure. The LTER-Belgium network also includes an agricultural ICOS site (Lonzée). One LTER-site belongs to the Ocean stations of ICOS, which is the VLIZ Data Buoy near the Thornton bank wind turbine farm in the North Sea (LTER_EU_BE_10). It collects data that will help to describe the biogeochemical status of the Belgian Coastal Waters. Within the ICOS project an infrastructure for coordinated, integrated, long-term high-quality observational data of the greenhouse balance of Europe is being built. This network endeavors to create the scientific backbone for a better understanding and quantification of greenhouse gas sources and sinks and their feedback with climate change. Challenges for the LTER network can lay in linking biodiversity aspects to this field of research.

TreeDivNet is a third international network where LTER-Belgium sites are involved. It concerns the FORBIO sites of Zwevezele, Hechel-Eksel and Gedinne. TreeDivNet is a global network of tree diversity experiments, which provides a unique platform for research on the relation between tree species diversity and ecosystem functioning in major forest types around the world. TreeDivNet currently consists of 18 experiments, distributed oer 36 sites and five ecoregions across the world (Verheyen et al. 2016).

The three above mentioned networks are examples of networks that are up and running and which form a solid backbone on which **LTER-Europe** can build. On the other hand, LTER -Europe is creating subnetworks. For example, since 2012 **Task Force on Marine and Transitional Waters**. It comprises 30 sites distributed across most of European seas, among which the two Belgian LTSER-platforms of the Belgian Coastal Waters and Sand Bank Systems (LTER_EU_BE_10) and the Scheldt Estuary and its Alluvial Plains (LTER_EU_BE_06). The broad commitment is fostering interactions and integrations among the LTER-Europe marine and transitional waters sites for a better and more active contribution to the LTER-Europe network. This includes promoting the exchange of knowledge of best practice for accessibility to research facilities, instrumentation, analytical methods and archiving of data in databases.

Other possibilities lay in the transboundary LTER-sites between Belgium and the Netherlands such as the Scheldt Estuary or the Heathland reserve De Zoom – Kalmthoutse Heide (LTER_EU_BE_08).

At the level of the **International Long Term Ecological Research Network (ILTER)** several multi-site research projects have been initiated. One example is the Tea Bag Index decomposition experiment in which several of our LTER-Belgium sites will take part.

Finally but not least, the trend at the European level towards the development of integrated research infrastructures in order to provide answers to the Grand Challenges may influence the directions of the LTER networks at national and international level. European demonstration projects, such as the eLTER H2020 project, are exploring the potential of the LTER network as a recruitment pool for fully integrated and hightly equipped research sites to conduct in depth long-term ecosystem research, now and in the future.

6 Further reading

Adriaenssens S, Staelens J, Baeten L, Verstraeten A, Boeckx P, Samson R, Verheyen K, 2013. Influence of canopy budget model approaches on atmospheric deposition estimates to forests. BIOGEOCHEMISTRY 116:215–229. http://dx.doi.org/10.1007/s10533-013-9846-0

Camino-Serrano M, Graf Pannatier E, Vicca S et al., Trends in soil solution dissolved organic carbon (DOC) concentrations across European forests. BIOGEOSCIENCES, http://dx.doi.org/10.5194/bg-2015-632, in review, 2016.

Cools N, De Vos B, 2011. Availability and evaluation of European forest soil monitoring data in the study on the effects of air pollution on forests. iFOREST 4:205−211. http://dx.doi.org/10.3832/ifor0588-004

Cools N, Delanote V, Scheldeman X, Quataert P, De Vos B, Roskams P, 2004. Quality assurance and quality control in forest soil analyses: a comparison between European soil laboratories. ACCREDIT QUAL ASSUR 9:688–694. http://dx.doi.org/10.1007/s00769-004-0856-4

Cools N, Vesterdal L, De Vos B, Vanguelova E, Hansen K, 2014. Tree species is the major factor explaining C:N ratios in European forest soils. FOREST ECOL MANAG 311:3–16. http://dx.doi.org/10.1016/j.foreco.2013.06.047

De Vos B, Cools N, Ilvesniemi H, Vesterdal L, Vanguelova E, Carnicelli, 2015. Benchmark values for forest soil carbon stocks in Europe: results from a large scale forest soil survey. GEODERMA 251−252:33−46. http://dx.doi.org/10.1016/j.geoderma.2015.03.008

Ferretti M, Calderisi M, Marchetto A et al., 2015. Variables related to nitrogen deposition improve defoliation models for European forests. ANN FOR SCI 72:897−906. http://dx.doi.org/10.1007/s13595-014-0445-6

Gielen B, De Vos B, Campioli M, Neirynck J, Papale D, Verstraeten A, Ceulemans R, Janssens IA, 2013. Biometric and eddy covariance-based assessment of decadal carbon sequestration of a temperate Scots pine forest. AGR FOREST METEOROL 174–175:135–143. http://dx.doi.org/10.1016/j.agrformet.2013.02.008

Gómez-González Y, Wang W, Vermeylen R, Chi X, Neirynck J, Janssens IA, Maenhaut W, Claeys M, 2012. Chemical characterisation of atmospheric aerosols during a 2007 summer field campaign at Brasschaat, Belgium: sources and source processes of biogenic secondary organic aerosol. ATMOS CHEM PHYS 12:125−138. http://dx.doi.org/10.5194/acp-12-125-2012

Jonard M, Andre F, Dambrine E et al., 2009. Temporal trends in the foliar nutritional status of the French, Walloon and Luxembourg broad-leaved plots of forest monitoring. ANN FOR SCI 66:412. http://dx.doi.org/10.1051/forest/2009014

Jonard M, Fürst A, Verstraeten A et al., 2015. Tree mineral nutrition is deteriorating in Europe. GLOBAL CHANGE BIOLOGY 21:418–430. http://dx.doi.org/10.1111/gcb.12657

Jonard M, Legout A, Nicolas M et al., 2012. Deterioration of Norway spruce vitality despite a sharp decline in acid deposition: a long-term integrated perspective. GLOBAL CHANGE BIOLOGY 18:711−725. http://dx.doi.org/10.1111/j.1365-2486.2011.02550.x

Neirynck J, Ceulemans R, 2008. Bidirectional ammonia exchange above a mixed coniferous forest. ENVIRON POLLUT 154:424−438. http://dx.doi.org/10.1016/j.envpol.2007.11.030

Neirynck J, Flechard CR; Fowler D, 2011. Long-term (13 years) measurements of SO_2 fluxes over a forest and their control by surface chemistry. AGR FOREST METEOROL 151:1768−1780. http://dx.doi.org/10.1016/j.agrformet.2011.07.013

Neirynck J, Gielen B, Janssens IA, Ceulemans R, 2012. Insights into ozone deposition patterns from decade-long ozone flux measurements over a mixed temperate forest. J ENVIRON MONITOR 14:1684−1695. http://dx.doi.org/10.1039/C2EM10937A

Neirynck J, Janssens IA, Roskams P, Quataert P, Verschelde P, Ceulemans R, 2008. Nitrogen biogeochemistry of a mature Scots pine forest subjected to high nitrogen loads. BIOGEOCHEMISTRY 91:201–222. http://dx.doi.org/10.1007/s10533-008-9280-x

Neirynck J, Kowalski AS, Carrara A et al., 2005. Driving forces for ammonia fluxes over mixed forest subjected to high deposition loads. ATMOS ENVIRON 39:5013−5024. http://dx.doi.org/10.1016/j.atmosenv.2005.05.027

Neirynck J, Kowalski AS, Carrara A, Genouw G, Berghmans P, Ceulemans R, 2007. Fluxes of oxidised and reduced nitrogen above a mixed coniferous forest exposed to various nitrogen emission sources. ENVIRON POLLUT 149:31−43. http://dx.doi.org/10.1016/j.envpol.2006.12.029

Neirynck J, Van Ranst E, Roskams P, Lust N, 2002. Impact of decreasing throughfall depositions on soil solution chemistry at coniferous monitoring sites in northern Belgium. FOREST ECOL MANAG 160:127−142. http://dx.doi.org/10.1016/S0378-1127(01)00476-5

Nussbaumer A, Waldner P, Etzold S et al., 2016. Patterns of mast fruiting of common beech, sessile and common oak, Norway spruce and Scots pine in Central and Northern Europe. FOREST ECOL MANAG 363:237–251. http://dx.doi.org/10.1016/j.foreco.2015.12.033

Schaubroeck T, Deckmyn G, Neirynck J, Staelens J, Adriaenssens S, Dewulf J, Muys B, Verheyen K, 2014. Multi layered Modeling of Particulate Matter Removal by a Growing Forest over Time, From Plant Surface Deposition to Washoff via Rainfall. ENVIRON SCI TECHNOL 48:10785−10794. http://dx.doi.org/10.1021/es5019724

Suz LM, Benham S, Dietrich H-P et al., 2014. Environmental drivers of ectomycorrhizal communities in Europe's temperate oak forests. MOL ECOL 23(22):5628–5644. http://dx.doi.org/10.1111/mec.12947

Talkner U, Meiwes KJ, Potočić N, Seletković I, Cools N, De Vos B, Rautio P, 2015. Phosphorus nutrition of beech (*Fagus sylvatica* L.) is decreasing in Europe. ANN FOR SCI 72:919–928. http://dx.doi.org/10.1007/s13595-015-0459-8

Van Ranst E, De Coninck F, Roskams P, Vindevogel N, 2002. Acid-neutralizing capacity of forest floor and mineral topsoil in Flemish forests (North Belgium). FOREST ECOL MANAG 166:45–53. http://dx.doi.org/10.1016/S0378-1127(01)00677-6

Verstraeten A, De Vos B, Neirynck J, Roskams P, Hens M, 2014. Impact of air-borne or canopy-derived dissolved organic carbon (DOC) on forest soil solution DOC in Flanders, Belgium. ATMOS ENVIRON 83:155–65. http://dx.doi.org/10.1016/j.atmosenv.2013.10.058

Verstraeten A, Neirynck J, Genouw G, Cools N, Roskams P, Hens M, 2012. Impact of declining atmospheric deposition on forest soil solution chemistry in Flanders, Belgium. ATMOS ENVIRON 62:50–63. http://dx.doi.org/10.1016/j.atmosenv.2012.08.017

Verstraeten A, Verschelde P, De Vos B, Joan Neirynck J, Cools N, Roskams P, Hens M, Louette G, Sleutel S, De Neve S. 2016. Increasing trends of dissolved organic nitrogen (DON) in temperate forests under recovery from acidification in Flanders, Belgium. SCI TOTAL ENVIRON 553: 107-119. http://dx.doi.org/10.1016/j.scitotenv.2016.02.060

Waldner P, Thimonier A, Graf Pannatier E et al., 2015. Exceedance of critical loads and of critical limits impacts tree nutrition across Europe. ANN FOR SCI 72:929–939. http://dx.doi.org/10.1007/s13595-015-0489-2

Waldner P, Marchetto A, Thimonier A et al., 2014. Detection of temporal trends in atmospheric deposition of inorganic nitrogen and sulphate to forests in Europe. ATMOS ENVIRON 95:363–74. http://dx.doi.org/10.1016/j.atmosenv.2014.06.054

7 References

Camino-Serrano M, Graf Pannatier E, Vicca S et al., Trends in soil solution dissolved organic carbon (DOC) concentrations across European forests. BIOGEOSCIENCES, http://dx.doi.org/10.5194/bg-2015-632, in review, 2016.

CLRTAP, 2014. Mapping Critical Levels for Vegetation, Chapter III of Manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends. UNECE Convention on Long-range Transboundary Air Pollution. www.icpmapping.org

De Temmerman L, Overloop S, 1999. Comparative measurements of concentrations and depositions of ammoniacal nitrogen on the measuring tower of Brasschaat. Communications Institute for Forestry and Game Management 1999 (in Dutch), pp. 89−101.

Flechard CR, Nemitez E, Smith RI et al., 2011. Dry deposition of reactive nitrogen to European ecosystems. ATMOS CHEM PHYS 11:2703–2728. http://dx.doi.org/10.5194/acp-11-2703-2011

ICP Forests, 2010. Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. UNECE, ICP Forests, Hamburg 2010. http://icp-forests.org/Manual.htm

Haase P, 2016. The long-term ecological research (LTER) network: Relevance, current status, future perspective and examples from marine, freshwater and terrestrial long-term observation. ECOL INDIC 65, 1 – 3.

IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006, First Update 2007. World Soil Resources Report No. 103. FAO, Rome.

Karlsson PE, Braun S, Broadmeadow M et al., 2007. Risk assessments for forest trees: The performance of the ozone flux versus the AOT concepts. ENVIRON POLLUT 146:608−616. http://dx.doi.org/10.1016/j.envpol.2006.06.012

Goldstein AH, McKay M, Kurpius MR, Schade GW, Lee A, Holzinger R, Rasmussen RA, 2004. Forest thinning experiment confirms ozone deposition to forest canopy is dominated by reaction with biogenic VOCs. GEOPHYS RES LETT 31. http://dx.doi.org/10.1029/2004GL021259

Gómez-González Y, Wang W, Vermeylen R, Chi X, Neirynck J, Janssens IA, Maenhaut W, Claeys M, 2012. Chemical characterisation of atmospheric aerosols during a 2007 summer field campaign at Brasschaat, Belgium: sources and source processes of biogenic secondary organic aerosol. ATMOS CHEM PHYS 12:125−138. http://dx.doi.org/10.5194/acp-12-125-2012

Holzke C, Hoffmann T, Jaeger L, Koppmann R, Zimmer W, 2006. Diurnal and seasonal variation of monoterpene and sesquiterpene emissions from Scots pine (*Pinus sylvestris* L.). ATMOS ENVIRON 40:3174−3185. http://dx.doi.org/10.1016/j.atmosenv.2006.01.039

Jactel H, Petit J, Desprez-Loustau M-L, Delzon S, Piou D, Battisti A, Koricheva J, 2012. Drought effects on damage by forest insects and pathogens: a meta-analysis. GLOB CHANGE BIOL 18, 267-276. http://dx.doi.org/10.1111/j.1365-2486.2011.02512.x

Janson RW, 1993. Monoterpene emissions from Scots pine and Norwegian spruce, J GEOPHYS RES-ATMOS 98:2839–2850. http://dx.doi.org/10.1029/92JD02394

Mellert KH, Göttlein A, 2012. Comparison of new foliar nutrient thresholds derived from van den Burg's literature compilation with established central European references. EUR J FOREST RES 131:1461–1472. http://dx.doi.org/10.1007/s10342-012-0615-8

Michel A., Seidling W. (eds.) 2015. Forest Condition in Europe, 2015 Technical Report of ICP Forests. Report under the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). Vienna: BFW Austrian Research Centre for Forests. BFW Dokumentation 21/2015. 182 p. http://icp-forests.net/page/icp-forests-technical-report

Monks PS, Archibald AT, Colette A et al., 2015. Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. ATMOS CHEM PHYS 15:8889−8973. http://dx.doi.org/10.5194/acp-15-8889-2015

Neirynck J, Gielen B, Janssens IA, Ceulemans R, 2012. Insights into ozone deposition patterns from decade-long ozone flux measurements over a mixed temperate forest. J ENVIRON MONITOR 14:1684−1695. http://dx.doi.org/10.1039/C2EM10937A

Neirynck J, Kowalski AS, Carrara A, Genouw G, Berghmans P, Ceulemans R, 2007. Fluxes of oxidised and reduced nitrogen above a mixed coniferous forest exposed to various nitrogen emission sources. ENVIRON POLLUT 149:31−43. http://dx.doi.org/10.1016/j.envpol.2006.12.029

Nussbaumer A, Waldner P, Etzold S, et al., 2016. Patterns of mast fruiting of common beech, sessile and common oak, Norway spruce and Scots pine in Central and Northern Europe. FOREST ECOL MANAG 363:237–251. http://dx.doi.org/10.1016/j.foreco.2015.12.033

Pilegaard K, Skiba U, Ambus P, et al., 2006. Factors controlling regional differences in forest soil emission of nitrogen oxides (NO and N_2O). BIOGEOSCIENCES 3:651−661. http://dx.doi.org/10.5194/bg-3-651-2006

Vanhellemont M, Verheyen K, 2011. Bos onder de loep, 40 jaar onderzoek in het Aelmoeseneiebos, uitg. Academia Press, Gent, 141 p.

Venterea RT, Groffman PM, Verchot LV, Magill AH, Aber JD, 2004. Gross nitrogen process rates in temperate forest soils exhibiting symptoms of nitrogen saturation. FOREST ECOL MANAG 196:129−142. http://dx.doi.org/10.1016/j.foreco.2004.03.016

Verheyen K, Vanhellemont M, Auge H, Baeten L, Baraloto C, Barsoum N, Bilodeau-Gauthier S, Bruelheide H, Castagneyrol B, Godbold D, Haase J, Hector A, Jactel H, Koricheva J, Loreau M, Mereu S, Messier C, Muys B, Nolet P, Paquette A, Parker J, Perring M, Ponette Q, Potvin C, Reich P, Smith A, Weih M, Scherer-Lorenzen M (2016) Contributions of a global network of tree diversity experiments to sustainable forest plantations. Ambio 45: 29-41
http://dx.doi.org/10.1007/s13280-015-0685-1

Verstraeten A, De Vos B, Neirynck J, Roskams P, Hens M, 2014. Impact of air-borne or canopy-derived dissolved organic carbon (DOC) on forest soil solution DOC in Flanders, Belgium. ATMOS ENVIRON 83:155–65. http://dx.doi.org/10.1016/j.atmosenv.2013.10.058

Verstraeten A, Neirynck J, Genouw G, Cools N, Roskams P, Hens M, 2012. Impact of declining atmospheric deposition on forest soil solution chemistry in Flanders, Belgium. ATMOS ENVIRON 62:50–63. http://dx.doi.org/10.1016/j.atmosenv.2012.08.017

Verstraeten A, Verschelde P, De Vos B, Joan Neirynck J, Cools N, Roskams P, Hens M, Louette G, Sleutel S, De Neve S. 2016. Increasing trends of dissolved organic nitrogen (DON) in temperate forests under recovery from acidification in Flanders, Belgium. SCI TOTAL ENVIRON 553: 107-119. http://dx.doi.org/10.1016/j.scitotenv.2016.02.060

Wagner D, 2009. Climate change effects on greenhouse gas emissions from Northern European soils. Diplomarbeit, University of Vienna. Fakultät für Geowissenschaften, Geographie und Astronomie.

Zanella A, Jabiol B, Ponge JF et al., 2011. A European morphofunctional classification of humus forms. GEODERMA 164:138–45. http://dx.doi.org/10.1016/j.geoderma.2011.05.016