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Preface to the special issue on integrated research of atmosphere, ecosystems and environment at Pallas

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The Pallas area in northern Finland has served as a meteorological monitoring site for 80 years and, more recently, as a platform for atmospheric, ecological and hydrological research. Currently, Pallas comprises one of the most important research infrastructures in Finland and in the wider circumpolar region. Moreover, it is a successful example of the benefits obtained from scientific cooperation and integration among disciplines. This paper is an introduction to a special issue that collates studies related to greenhouse gas fluxes and concentrations, atmospheric aerosols and air pollutants, which were presented at the Fourth Pallas Symposium held in 2013. We give an overview of the historical and current research activities within the Pallas area, outline the most important infrastructure projects and list the recent literature that has originated from the various scientific programs and projects. The results of these activities are illustrated in this paper with examples of long-term data sets on variations in soil, lake and river water, air quality and greenhouse gas concentrations.

Pallas area as a meeting point of nature heritage and top science

The Pallas fells, located approximately 170 km north of the Arctic Circle, rise to an elevation of 500–800 m above sea level (a.s.l.); the highest summit, Taivaskero, reaches 809 m a.s.l. The fells belong to the 50-km-long fell chain of Pallas–Ounastunturit (the Finnish word *tunturi*, used here as a suffix, means “fell”). Pallasjärvi is the largest lake within the area, has an area of 17.3 km^2 and drains to the Baltic Sea via the rivers Ounasjoki and Kemijoki (the Finnish words *järvi* and *joki*, used here as suffixes, mean "lake" and "river", respectively). The mean and maximum depths of Pallasjärvi are 9 and 36 m, respectively. The Keimiötunturi, Sammaltunturi and Pallastunturi are composed of mafic volcanic rock types, thus giving rise to nutrient rich soil conditions on the fell slopes. The treeline conifer species is the Norway spruce, which is found at 457 m a.s.l. on the Lommoltunturi and at 530–548 m a.s.l. on Keimiötunturi. In contrast, the treeline conifer on the nutrient-poor, felsic Ounastunturi is the Scots pine at 360 m a.s.l. (Sutinen *et al*. 2011). As a consequence of the warming climate in the region since the 1920s, a significant shift of spruce has occurred such that the tree line has extended in elevation by 55 m in 60 years (Sutinen *et al*. 2012).

According to the Köppen climate classification, the Pallas region is located at the edge of the northern-boreal and subarctic climatic zones. The winters are cold and the summers short and cool with long-term monthly mean temperatures of –14 °C and +14 °C in January and July, respectively. The long-term annual mean temperature (1981–2010) measured at the Alamuonio weather station located ca. 35 km west of Pallas is –1.0 °C (Pirinen *et al*. 2012). The average peak snow depth reaches 73 cm and is typically observed during the latter half of March. Pallas can be considered to also lie on the border of anthropogenic influences: to the south there is densely populated, continental Europe, while to the east and north there are mainly large, sparsely-populated areas dominated by tundra and the Arctic Ocean, respectively. Although the first air quality measurements at Pallas were motivated by the industrial emissions from the Kola Peninsula (Russia), the area is one of the least polluted parts of continental Europe and thus the data from the Pallas sites are often considered to represent "background conditions".

The Pallastunturit area was designated as a National Park in 1938. While the National Park initially covered the Pallas-Ounastunturi region, in 2005 it was expanded to include the southern fell area of Yllästunturit as well. The Pallas-Yllästunturi National Park currently covers an area of 1020 km^2. On 6 July 1952, the Olympic flame ignition for the Helsinki Olympic Games took place at the summit of the Taivaskero fell.

The Finnish Meteorological Institute (FMI; Finnish Meteorological Office before 1968) has a long history of atmospheric monitoring at Pallas. The first weather station "Pallasjärvi" (site 6c in Fig. 1) was established near Pallasjärvi in 1935 with three daily weather observations (Fig. 2a). The operation of this station ceased in 1972, four years after the retirement of Mr. Viljo Pakasmaa, the station manager and the park ranger of the Pallas-Ounastunturi National Park (Fig. 2b). The only significant gap in the observation records between 1935 and 1972 was from the autumn of 1944 to the winter of 1946 as the residence of the park ranger at Pallasjärvi was destroyed in the final stages of World War II (Keränen and Väisälä 1938, Hiilivirta and Hiilivirta 2011). The weather station was in operation again from 1996 until 2002, thereafter the measurements were moved to the newly established Kenttärova station.

The Pallas research infrastructure has been extensively instrumented for modern and versatile monitoring of the environment since the start of continuous monitoring of atmospheric sulphur dioxide (SO_2) and ozone (O_3) concentrations at Sammaltunturi in September 1991, and with the setup of the Global Atmosphere Watch (GAW) station in 1994. The measurement sites have contributed to numerous European and global research programs and research infrastructures (Table 1). In 2009, the Academy of Finland recognized Pallas (together with the FMI Arctic research Centre at Sodankylä) as one of the most significant national research infrastructures in Finland. Since 2015, the measurements of greenhouse gas (GHG) concentrations and ecosystem-atmosphere fluxes have been part of the Integrated Carbon Observation System (ICOS). Pallas has also been nominated as a strong candidate for the European-wide ecosystem experimentation infrastructure (AnAEE). Thus Pallas is unquestionably one of the most important climate and ecosystem research stations in northern Europe and within the wider circumpolar region.

This special issue of *Boreal Environment Research* covers a wide spectrum of research that takes place at Pallas. It was conceived in Septem-

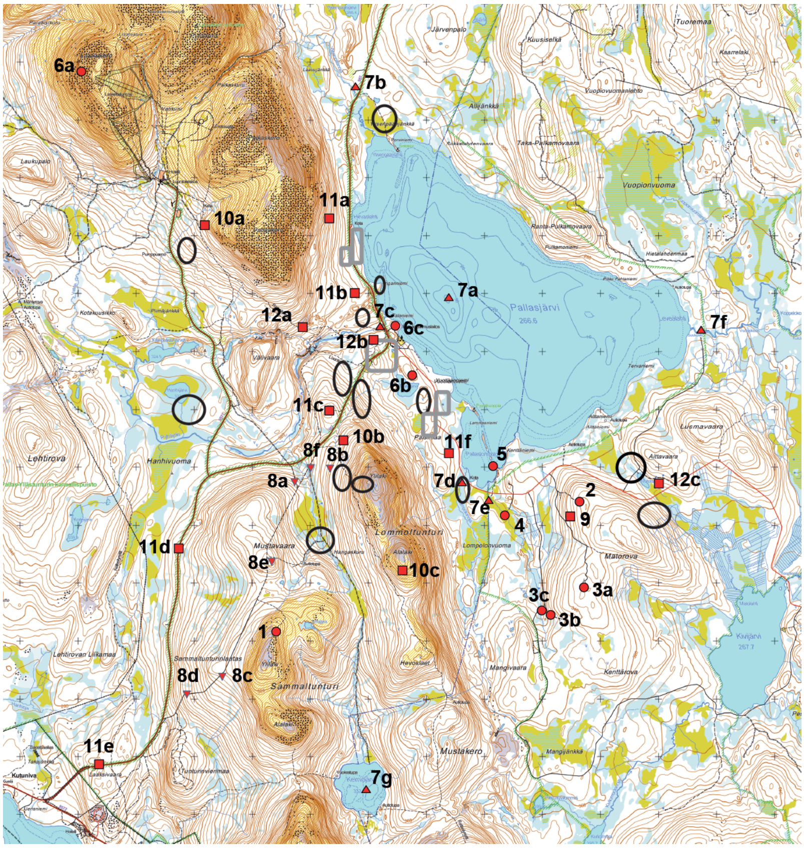

Fig. 1. Map of the Pallas area showing the measurement stations. Explanations are provided in Tables 2 and 3, except for sites 6a, b and c which are the Laukukero weather station, Pallasjärvi automatic weather station (1996–2002) and Pallasjärvi manual weather station (1935–1972), respectively. Red circles, upward triangles and downward triangles represent FMI, SYKE and GTK measurement sites and sampling points, respectively. The main study sites for small-mammal research around Pallasjärvi are indicated as follows: black circles and ovals indicate the long-term, continuous monitoring sites (since 1970), and gray rectangles indicate various experimental sites with live-trapping programs. Other, more irregular mammal sampling sites are not shown.

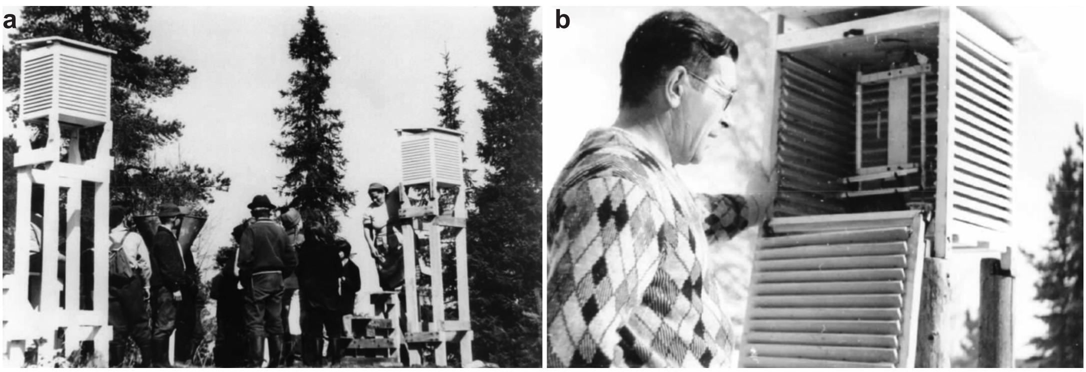

Fig. 2. (**a**) Mrs. Esteri Pakasmaa (née Kotakorva) making meteorological observations at the Pallasjärvi weather station in 1963. Local school children are following the procedure. (**b**) Mr. Viljo Pakasmaa beside the instrument shelter at Pallasjärvi in 1965. The shelter contains a thermometer to measure the ambient temperature, a wet-bulb thermometer for obtaining the dew point of the air, and a minimum–maximum thermometer for daily minimum and maximum temperatures. Photos: Ms. Sofia Pyykönen's family album via Pallastunturi Nature Centre.

ber 2013 during the Fourth Pallas Symposium, which was organized at Hotel Jeris, Muonio, in the inspiring surroundings of Jerisjärvi, which is adjacent to the Pallas-Yllästunturi National Park. The symposium brought together 45 scientists from different disciplines, which included e.g. geology, environmental science, atmospheric science, hydrology and biology. The earlier Pallas

Symposia in 1988, 1996 and 1998 dealt mainly with the role of research within nature reserves. In 1988, the first symposium examined recent and current studies in nature conservation areas around the country. The topics of the first symposium ranged from basic cartography in the natural sciences to environmental economics (http://www.metla.fi/tapahtumat/2013/pallas-symposium/folia-forestalia-736.pdf). The second symposium in 1996 was still focused mainly on the role of the Pallas-Ounastunturi National Park in monitoring global environmental changes, although topics related to climate change were already emerging (http://www.metla.fi/julkaisut/mt/623/index.htm). The topics of the third symposium were concentrated on the role of the National Park in literature and visual arts (http://www.metla.fi/julkaisut/mt/735/index.htm). As an outcome of this meeting, a book entitled "Pallas-Ounas" was published (http://www.metla.fi/julkaisut/muut/annanpalo.htm). The key topic of the Fourth Symposium was the interactions between northern ecosystems and the various needs of human society with the main focus on recent trends and ecosystem functioning, and on the responses of northern ecosystems to chang-

Table 1. International measurement programs and research infrastructures to which the Pallas sites contribute.

Program/Infrastrucutre	Acronym	Sites included	Responsible institutes
Global Atmosphere Watch	GAW	Sammaltunturi	FMI
Aerosols, Clouds, and Trace gases Research Infrastructure	ACTRIS-2	Sammaltunturi, Matorova	FMI
International Arctic Systems for Observing the Atmosphere	IASOA	Sammaltunturi	FMI
Arctic Monitoring and Assessment Programme	AMAP	Sammaltunturi, Matorova Pallasjärvi	FMI, SYKE, IVL
The European Monitoring and Evaluation Programme	EMEP	Sammaltunturi, Matorova	FMI, IVL
International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests	ICP Forests	Matorova	LUKE
International Co-operative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems	ICP IM	Pallasjärvi and its catchment	SYKE, FMI, LUKE
Finnish Long-Term Socio-Ecological Research network	FinLTSER	Pallasjärvi and its catchment	SYKE, FMI, LUKE
Integrated Carbon Observation System	ICOS	Lompolojänkkä, Sammaltunturi	FMI
European Long-Term Ecosystem Research Network	LTER-Europe	Pallasjärvi and its catchment	SYKE, FMI, LUKE
International Long-Term Ecological Research Network	ILTER	Pallasjärvi and its catchment	SYKE, FMI, LUKE
EU Water Framework Directive	WFD	Keimiöjärvi, Pallasjärvi, Pallasjoki	SYKE, LUKE
Pan-Eurasian Experiment	PEEX	Sammaltunturi, Matorova	FMI
Global Mercury Observation System	GMOS	Matorova	FMI, IVL
Analysis and Experimentation in Ecosystems (under construction)	AnaEE	candidates: Lompolojänkkä, Kenttärova	FMI

ing environment. Seven of the presentations of the symposium were expanded to full scientific papers presented in this special issue. This introductory paper gives an overview of the wide spectrum of research conducted at Pallas, and lists the most recent published literature.

Overview of the research sites and topics

A wide range of environmental research is conducted within the Pallas area by the FMI, the Natural Resources Institute Finland (LUKE), the Finnish Environment Institute (SYKE) and the Geological Survey of Finland (GTK). The main research topics include GHG concentrations and ecosystem–atmosphere fluxes, the climate effects of atmospheric aerosols, aerosol–cloud interactions and air quality (FMI), the effects of air pollution on ecosystems, climate effects on both hydrology and physical, chemical and biological chracteristics of surface waters, and the deposition of persistent organic pollutants (POPs) (SYKE). At the aquatic sites — Pallasjärvi, Keimiöjärvi and Pallasjoki — LUKE is responsible for collecting fish status data for surveillance monitoring and ecological classification according to the EU Water Framework Directive. LUKE also monitors population dynamics, parasites and pathogens of small rodents, forest condition (ICP Forests), dynamics of natural forests and timberline forests, and the timing of spring and autumn phenophases. GTK is currently studying soil hydrological changes with a particular interest in snow accumulation, snowmelt and soil freezing mechanisms, which are related to treeline dynamics. Pallas also serves as one of the sites of the Finnish network for monitoring the concentrations of mercury and other heavy metals, benzo(*a*)pyrene, O_3 and other air pollutants as required by the European legislation on ambient air quality assessment and management.

In addition to the engagement of several national institutes, there is active cooperation with foreign institutes and universities, such as the Swedish Environmental Research Institute (IVL), the US National Oceanic and Atmospheric Administration (NOAA), and Royal Holloway University of London, UK.

There are several research stations and measurement sites established within the area, the most prominent of which is the log cabin constructed by the former Finnish Forest Research Institute (METLA, now part of LUKE) and the FMI at the summit of the Sammaltunturi (Fig. 1). Other measurement sites, typically smaller log or fiberglass cabins and shelters, or just sample-collection instruments, are spread over a relatively small area mainly south of Pallasjärvi.

The Pallas area comprises five official FMI weather stations: Matorova (established in 1995), Laukukero (1996), Sammaltunturi (1996), Kenttärova (2002) and Lompolonvuoma (2013). The latter is actually situated on the Lompolojänkkä mire on the premises of the GHG flux station, but it is named according to the adjacent wetland west of Lompolojänkkä. The main meteorological variables recorded at these stations are air temperature, relative humidity, wind speed and wind direction. In addition, soil temperature and moisture, air pressure, snow depth, precipitation and solar radiation are measured at Kenttärova and Lompolojänkkä (for details *see* tables 2 and 3 in Aurela *et al*. 2015).

While the Laukukero station (site 6a in Fig. 1) mainly provides meteorological outputs with occasional measurement campaigns for other variables, the other stations host a wide spectrum of different research activities. Four GHG flux stations at Pallas are partly co-located with the weather stations: Kenttärova spruce forest (GHG flux measurements established in 2003), Lompolojänkkä wetland (2005), Pallaslompolonniemi at Pallasjärvi (2014) and Sammaltunturi (2013). Measurements at these sites include the exchange of carbon dioxide (CO_2), water vapor and energy between the atmosphere and the local ecosystem. At some stations, methane (CH_4) exchange is also measured. These data make it possible to quantify the GHG balances of the major ecosystems within the area (Aurela *et al*. 2015). In addition to GHG fluxes, many additional meteorological and hydrological measurements are conducted to facilitate the interpretation of the flux data. These measurements are detailed in table 2 of Aurela *et al*. (2015).

The **Sammaltunturi** station (site 1 in Fig. 1) is located at an elevation of 565 m a.s.l. at the summit of the second southernmost fell along the 50-km-long north–south chain of fells. The station resides ca. 100 m above the treeline. The vegetation around the station consists mainly of low vascular plants, mosses and lichen. Monitoring activities at Sammaltunturi began in 1991 in a building that originally served the Finnish Broadcasting Company. The new, 102-m^2 station opened in July 2001. Since 1994, Sammaltunturi has been a node of the Pallas–Sodankylä supersite that contributes to the GAW program of the World Meteorological Organization. The GAW measurements at Sammaltunturi focus on tropospheric air composition and meteorology, while upper-air ozone soundings and measurements of aerosol optical depth and spectral UV, for example, are operated by the FMI Arctic Research Centre at Sodankylä (125 km SE from Pallas). As the Pallas area has no significant local or regional air pollution sources, Sammaltunturi provides an excellent location for the monitoring of the background air composition in northern Europe. The measurements conducted at Sammaltunturi and other sites are detailed in Table 2.

The **Matorova** station (site 2 in Fig. 1) lies 6 km ENE of Sammaltunturi at an elevation of 340 m a.s.l. The station is mainly used to collect deposition, gas and aerosol samples. Special attention is paid to minimize contamination of the samples collected for trace metal, mercury and POP analyses. This extends to the selection of the materials for the station building and to the wooden walking trails constructed to prevent wind-driven erosion. In addition, usage of motor vehicles close to the station is limited as much as possible. A Level II intensive monitoring site of the International Co-operative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests (**ICP Forests**, site 9) is located in the close vicinity of the Matorova station.

The **Kenttärova** station (site 3a in Fig. 1), which includes a 20-m high measurement tower, was established in 2002 to study atmosphere–biosphere interactions above a Norway spruce forest. For synergy, the FMI Observation Services moved the old Pallasjärvi weather station, located 5 km to the northwest, onto the premises of Kenttärova. The Kenttärova station lies on a hilltop plateau, 1.4 km south of the Matorova station, ca. 60 m above the surrounding plains. Kenttärova is well known for often having the thickest snow cover among the Finnish weather stations. A more detailed description of the site is given in Aurela *et al*. (2015).

The **Lompolojänkkä** (site 4 in Fig. 1) flux station was built in 2005 to measure CO_2 and CH_4 exchange between the wetland and the atmosphere (Aurela *et al*. 2015). It is located on a treeless open mire through which the waters from the Kenttärova catchment discharge to Pallasjärvi. This aapa mire is characterized by a relatively high water level, with almost the entire peat profile being water-saturated throughout the year (Aurela *et al*. 2009, Lohila *et al*. 2010). The maximum peat thickness is 3 m. Peat cores and their macrofossil and radiocarbon analyses have revealed that peatlands started to develop immediately after the retreat of the ice about 10 000 years ago. Since then, the mire has been growing both horizontally and vertically (Mathijssen *et al*. 2014). In 2008, a drying and warming experiment was set up at Lompolojänkkä by LUKE to quantify the effects of the predicted climate change, i.e. warming, water-level drawdown and their interactions, on the functioning of the fen ecosystem (Pearson *et al*. 2015).

The **Pallaslompolonniemi** (site 5 in Fig. 1) flux station was established in order to measure gas and energy fluxes between Pallasjärvi and the atmosphere. A 2-m-tall steel mast was erected in June 2012 at the tip of a small spit, a beautiful site which is also known as an ancient hunting and fishing site of the Sami people. The spit is part of an esker gravel ridge that is partly located underwater. The ridge divides the area into a shallow and sheltered inlet (through which the surface waters from the Pallaslompolo catchment are discharged), and a deeper lake. The mean depths of the lake are approx. 1.5 and 5 m in the inlet and in the deeper parts, respectively. In addition to GHG fluxes, basic meteorological data and water temperature and level are measured at this site (Lohila *et al*. 2015, Aurela *et al*. 2015).

Pallasjärvi with its catchment (sites 7a–f in Fig. 1). SYKE conducts hydrological, chemical and biological monitoring at seven stations, including four main inlet streams, two lakes and a river. Keimiöjärvi (site 7g in Fig. 1) is located outside the catchment ca. 5 km south of Pallasjärvi. The main studies utilizing these measurements include air pollution effects on

Table 2. Main variables measured at the different Pallas subsites. The site location is shown according to the WGS-84 coordinates. Numbers in bold depict corresponding sites in Fig. 1.

Subsite	Variables	Measurement methods	Reference
Sammaltunturi (fell top), site 1 (67°58.400´N, 24°06.939´E, 565 m a.s.l.)			
FMI	Atmospheric CO_2, CH_4, N_2O, O_3, SO_2, $NO+NO_y$, SF_6, CO, H_2	On-site analyzers	Hatakka *et al.* 2003, Kilkki *et al.* 2015, Ruoho-Airola *et al.* 2015, Tsuruta *et al.* 2015
NOAA, US	Atmospheric CO_2, CH_4, CO, H_2, N_2O, SF_6, $\delta^{13}C$ (CO_2), $\delta^{18}O$ (CO_2)	Weekly flask samples	http://www.esrl.noaa.gov/gmd/ccgg/flask.php
Royal Holloway University of London, UK	Atmospheric delta ^{13}C (CH_4)	Weekly bag samples	Sriskantharajah *et al.* 2012
FMI	Atmospheric VOC	On-line GC	Hellén *et al.* 2015
FMI	Total and cloud interstitial aerosol number concentration and size distribution (7–500 nm)	2 × CPC, 2 × DMPS	Komppula *et al.* 2003, Kivekäs *et al.* 2009
FMI	Larger aerosol size distribution (0.5–10 μm)	APS	
FMI	Ion and neutral particle size distributions (0.4–40 nm)	NAIS	Lihavainen *et al.* 2007, Manninen *et al.* 2010
FMI	Aerosol hygroscopicity	H-TDMA	Anttila *et al.* 2009
FMI	Aerosol black carbon, scattering and absorption coefficients	Aethalometer, Nephelometer, MAAP	Aaltonen *et al.* 2006, Lihavainen *et al.* 2015
FMI	PM_{10} aerosol mass	Beta gauge	
FMI	^{222}Rn	Total beta activity	Paatero *et al.* 1994
FMI	CO_2, H_2O, sensible heat, momentum fluxes	Eddy covariance	Aurela *et al.* 2015
FMI	Phenology, cloudiness	Digital photography	
Kenttärova (spruce forest), site 3a (67°59.237´N, 24°14.579´E, 347 m a.s.l.)			
FMI	Atmospheric CO_2, CH_4, H_2O concentration profile in the canopy	On-site analyzer	
FMI	CO_2, H_2O, sensible heat, momentum fluxes	Eddy covariance	Aurela *et al.* 2015
FMI	Soil CH_4, N_2O fluxes	Manual chambers	
FMI	Cloud base height	Ceilometer	
FMI	Phenology	Digital photography	

continued

Table 2. Continued.

Subsite	Variables	Measurement methods	Reference
Lompolojänkkä (wetland), site 4 (67°59.835'N, 24°12.546'E, 269 m a.s.l.)			
FMI	CO_2, CH_4, H_2O, sensible heat, momentum fluxes	Eddy covariance	Aurela *et al.* 2009, 2015
FMI	CO_2, CH_4 fluxes (N_2O fluxes 2006– 2010)	Automatic chambers	Lohila *et al.* 2010
FMI, LUKE	CO_2, CH_4, N_2O fluxes	Manual chambers	Lohila *et al.* 2010, Pearson *et al.* 2015
FMI	CO_2, CH_4, concentrations in air (1 and 3 m) and in peat (0.15 m below the surface)	On-site analyzer	
FMI	O_3 concentrations in air	Automatic analyzer	
FMI	Phenology	Digital photography	
Pallasjärvi (lake) (68°0.280´N, 24°12.254´E, 267 m a.s.l.)			
FMI (site 5)	CO_2, H_2O, sensible heat, momentum fluxes	Eddy covariance	Lohila *et al.* 2015
SYKE (site 7a)	Lake water chemistry (high number of variables including major ions, nutrients, organic matter, trace metals[1)]) and biology[5)]. Water level and temperature of lake	Manual sampling, automatic measurements	Lohila *et al.* 2015
LUKE (site 7a)	Fish parameters for assessing the ecological status[6)]	CEN standardized sampling with NORDIC gillnets	Sairanen and Ruuhijärvi 2014
Catchment of Pallasjärvi			
SYKE (sites 7a–f)	Stream water chemistry[1)] of the four inlet streams and the outlet river of Palasjärvi (Pallasjoki). Biological monitoring[7)]. Discharge of lake inlet and outlet.	Manual sampling, automatic measurements	
LUKE (site 7f)	Pallasjoki. Fish parameters for ecological status[8)].	CEN standardized electrofishing	
University of Oulu (sites 3b–c, 4, 7e)	^{18}O in precipitation and stream water	Manual sampling	
FMI (sites 3b–c)	Stream water chemistry	Manual sampling	
Keimiöjärvi (lake), site 7g (67°57.198´N, 24°9.534´E, 332 m a.s.l.)			
SYKE	Lake water chemistry (high number of variables including major ions, nutrients, organic matter, trace metals[1)]) and biology[5)].	Manual sampling	
LUKE	Fish parameters for assessing the ecological status[6)]	CEN standardized sampling with NORDIC gillnets	Sairanen and Ruuhijärvi 2014

Matorova, site 2 (67°59.991´N, 24°14.399´E, 340 m a.s.l.)			
FMI	PM_{10} PAH, PM_{10} trace metals[4)], $PM_{2.5}$ major ions[2)], major ions and gases[3)]	Filter sampling	Paatero *et al.* 2009, Ruoho-Airola *et al.* 2015
FMI	Deposition samples: pH, conductivity, major ions[2)], mercury, trace metals[4)], PAH	Bulk collectors	Kyllönen *et al.* 2009, Cape *et al.* 2012, Ruoho-Airola *et al.* 2015
FMI	Gaseous mercury	Analyzer	Wängberg *et al.* 2010
IVL, Sweden	POPs	Filter sampling and bulk collectors	Hung *et al.* 2008
IVL, Sweden	Total gaseous and total particulate mercury	Gold traps	Wängberg *et al.* 2010
IVL, Sweden	Mercury deposition	Bulk collector	Wängberg *et al.* 2010
SYKE	POPs	Bulk collectors	Korhonen *et al.* 1998, Mannio *et al.* 2002
FMI	$PM_{2.5}$ aerosol mass	Beta gauge	
FMI	Elemental/organic carbon (EC/OC)	Thermo-optic analyzer	
LUKE (site 9)	Forest condition (ICP Forest)		Lindroos *et al.* 2006, 2008, Merilä and Derome 2008, Ukonmaanaho *et al.* 2008
Soil/water stations at Sammaltunturi, Lommoltunturi and Hangaskurunoja, (sites 8a–f)			
GTK	Soil water content, soil/air/snow temperature, snowpack thickness, snow water, precipitation; stream water pH, redox, conductivity, temperature; others: stream water chemistry	Five automatic and telemetric (Campbell/Decagon) stations since 2007. The oldest soil station established in 1998, updated in 2003.	Sutinen *et al.* 2009, 2011, Liwata *et al.* 2014
Ecological monitoring in the Pallas region			
LUKE (sites 10a–c, 11a–c)	Dynamics of natural forests and timberline forests		Seppänen and Norokorpi 1998, Varmola *et al.* 2001
LUKE (sites 12a–c)	Spring and autumn phenophases of trees and shrubs, monitoring of seed production and litterfall of forest trees		Kubin *et al.* 2006
LUKE (circles and rectangles in Fig. 1)	Dynamics of small rodent populations. Many long-term monitoring sites in different habitats around the Pallasjärvi–Lommoltunturi–Hanhivuoma–Matorova area		Henttonen *et al.* 1987, Henttonen 2000

1) Temperature, conductivity, pH, alkalinity, absorbance, O_2 concentration, O_2 percentage, turbidity, colour, chemical oxygen demand (CODMn), total P, PO_4-P, total N, NO_3-N, NH_4-N, Al, Fe, Mn, SiO_2, K, Ca, Mg, Na, SO_4, Cl, F, TOC, TIC, As, Ba, Cd, Co, Cr, Cu, Ni, Pb, Pd, Pt, Se, Sr, Ti, Zn, V, Hg.
2) SO_4, NO_3, Cl, Na, K, Ca, Mg, NH_4.
3) SO_2, SO_4, NO_3 + HNO_3, Cl, Na, K, Ca, Mg, NH_4 + NH_3 (EMEP 3-stage filter sampling).
4) Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V, Zn.
5) Chlorophyl *a*, phytoplankton, periphyton, benthic macroinvertebrates, macrophytes.
6) BPUE (total weight of fish/net), NPUE (total number of fish/net), biomass proportion of cyprinid fishes, occurrence of indicator species.
7) Periphyton, benthic macroinvertebrates.
8) Proportion of sensitive species, proportion of tolerant species, density of 0+ salmonids, proportion of cyprinids, number of species.

ecosystems, hydrological processes and climate change, and changes in leaching and material fluxes (C/N) in the catchment and the lake itself.

In 2004, continuous water level and surface water temperature recordings commenced in Pallasjärvi, as did the monitoring of discharge in the main inlet stream Pyhäjoki and the outlet stream Pallasjoki. Since 2012, water temperature recording has been supplemented by automatic temperature measurements in the whole water profile in the deep-water area (1-m depth interval, 2 measurements per hour). In addition, a small drainage basin (with an overflow-measuring weir) for monitoring of the runoff water chemistry and automatic runoff and dissolved organic matter (CDOM) recordings were established in **Lompolojänganoja** (site 7e) in 2013 and 2014, respectively, as part of the FMI's Lompolojänkkä site. The stream drains the Lompolojänkkä fen and the upper parts of the sub-catchment (*see* Aurela *et al*. 2015). In 2008, quantitative monitoring of the runoff flow from the Lompolojänkkä fen to Pallasjärvi was started by FMI and in 2013, SYKE upgraded the runoff measurement station by building a log cabin equipped with mains electricity. As part of the monitoring of hydrological processes, soil moisture recordings commenced in the Matorova area in 2014.

METLA carried out extensive fish monitoring in Pallasjärvi in 1990. The results of this gillnet survey were utilized when METLA and the fishing association of Raattama negotiated the future fishing policies for the lake. Based on gill raker counts, there were several morphs of the whitefish in Pallasjärvi, reflecting both the original stock and several man-made introductions with other stocks (H. Henttonen unpubl. data).

Fish status monitoring for the EU Water Framework Directive was commenced in Keimiöjärvi and Pallasjärvi in 2006 as part of the interregional project TRIWA (The River Torne International Watershed; Sairanen *et al*. 2008). Standard methods of CEN (European Committee for Standardization) have been used in the sampling of the lakes (NORDIC gillnets) and the Pallasjoki (electrofishing). In test fishing of Pallasjärvi in 2013, the most abundant fish species were the vendace (*Coregonus albula*), whitefish (*Coregonus lavaretus*), grayling (*Thymallus thymallus*) and burbot (*Lota lota*). All these species, as well as the littoral species — the alpine bullhead (*Cottus poecilopus*) and the nine-spined stickleback (*Pungitius pungitius*) — are sensitive to environmental changes, which highlights the value of Pallasjärvi as a monitoring site of high ecological status. Similarly, the dominance of the grayling and bullhead (*Cottus gobio*) in the electrofishing catches from the Pallasjoki in 2012, supported by other biological quality parameters examined by SYKE, indicated the high ecological status of the river.

The **Pallasjärvi** automatic weather station (site 6b) was in operation in 1996–2002. The station was located close to the northern shore of Palsijärvi (68°01´N, 24°10´E). The site also served as a platform for campaign-based measurements of radioactivity, for example (Paatero *et al*. 1998).

Sammaltunturi–Lommoltunturi/Hangaskurunoja (sites 8a–f). As a part of a national network, GTK established five automatic and telemetric soil monitoring stations in Sammaltunturi–Lommoltunturi and one stream-water station at Hangaskurunoja in 2007. However, the oldest soil station on the northern slope of Sammaltunturi was established in 1998 and updated in 2003. The focus of these sites is to follow the intra- and inter-annual soil hydrological changes with a particular interest in snow accumulation, snowmelt and soil freezing mechanisms. This is important for understanding the forest and treeline dynamics as well as for modeling the freeze-thaw effects on soil bearing capacity and infiltration in the watershed-scale (flooding) studies. The soil stations also provide information on spruce forest (south and north aspects), treeline and tundra conditions. In addition to the automatically recorded data, hydrological modeling requires input data on soil structure and texture down to a 1-m depth in the stratigraphic sequences. At the Hangaskurunoja station, the water cycle and the snowmelt effect on the water quality in particular are complemented by water chemistry analyses.

Daily deposition samples for the main inorganic ion analyses were collected at the **Särkijärvi** frontier guard station (67°55´N, 23°56´E) in 1991–1999. These observations were later continued at Matorova with weekly sampling periods (Leinonen 2000).

In addition to the permanent measurement stations, some of the ecological long-term monitoring studies take place at several subsites spread out around Pallas. One of the most famous of these is rodent monitoring (sites indicated with circles in Fig. 1), which makes use of the exceptionally diverse rodent fauna of the Pallas region: six vole and two lemming species are found sympatrically. In this respect, the Pallas region is of global interest. This diversity, observed in many animals and plant taxa, is attributed to the location of Pallas at the contact zone of many southern and northern elements. The Pallas rodent studies started in 1970 during the great lemming migration, and have continued since then, allowing for detailed long-term studies on various aspects of mammalian population ecology. The research includes long-term permanent monitoring sites, as well as replicated shorter-term experimental sites.

The main measured variables at the Pallas area (excluding meteorology which is detailed in Aurela *et al*. 2015) are listed in Tables 2 and 3.

Trends in soil, water and atmospheric parameters

In this section we present some examples of the long-term monitoring data collected at Pallas by the different institutes. While here we focus on the results from atmospheric and hydrological studies, there is a long list of papers on ecology, geology, microbiology and other subjects; most of which are listed in the references and the Appendix.

Soil water content

The Sammaltunturi soil stations provide intra- and inter-seasonal data to aid the understanding of soil freeze–thaw cycles and soil temperature variations along the elevation gradient (Sutinen *et al*. 2009). One of the recent observations indicates that — even though soil water content varies seasonally — the spatial pattern of the soil water content does not change with time when the observations are ranked according to the magnitude of the soil water (Fig. 3). This time-stability concept holds for a diversity of soils throughout the boreal climatic zones, including Sammaltunturi forest and treeline soils (Liwata *et al*. 2014).

Inflow and organic carbon in lakes and rivers

In 2004, SYKE established the Pallasjärvi catchment research infrastructure for intensive hydrological, chemical and biological monitoring of the Pallasjärvi catchment. One of the findings of the monitoring was that total organic carbon

Table 3. Chemical, hydrological and biological monitoring sites of SYKE and GTK and soil hydrological monitoring sites of GTK. LUKE conducts fish status monitoring at the biological monitoring sites.

Sampling site	Coordinates	Environment	Chemical monitoring	Hydrological monitoring	Biological monitoring
Pallasjärvi, site 7a	68°1.812´N, 24°10.872´E	Lake	+	+	+
Ylisenpäänoja, site 7b	68°3.714´N, 24°8.334´E	Inlet stream	+		
Pyhäjoki, site 7c	68°1.524´N, 24°9.318´E	Inlet stream	+	+	
Lompolonoja, site 7d	68°0.15´N, 24°11.508´E	Inlet stream	+		
Lompolojänganoja, site 7e	68°0.024´N, 24°12.102´E	Inlet stream	+	+	
Pallasjoki, site 7f	68°1.608´N, 24°17.202´E	Outlet river	+	+	+
Keimiöjärvi, site 7g	67°57.198´N, 24°9.534´E	Lake	+		+
Sammaltunturi N, site 8a	67°59.982´N, 24°7.356´E	Forest		+	
Lommoltunturi, site 8b	68°0.132´N, 24°7.944´E	Forest		+	
Sammaltunturi S, site 8c	67°58.176´N, 24°5.7´E	Treeline		+	
Sammaltunturi S, site 8d	67°58.014´N, 24°4.968´E	Forest		+	
Sammaltunturi, site 8e	67°59.298´N, 24°6.87´E	Tundra		+	
Hangaskurunoja, site 8f	68°0.102´N, 24°7.602´E	Inlet stream	+	+	

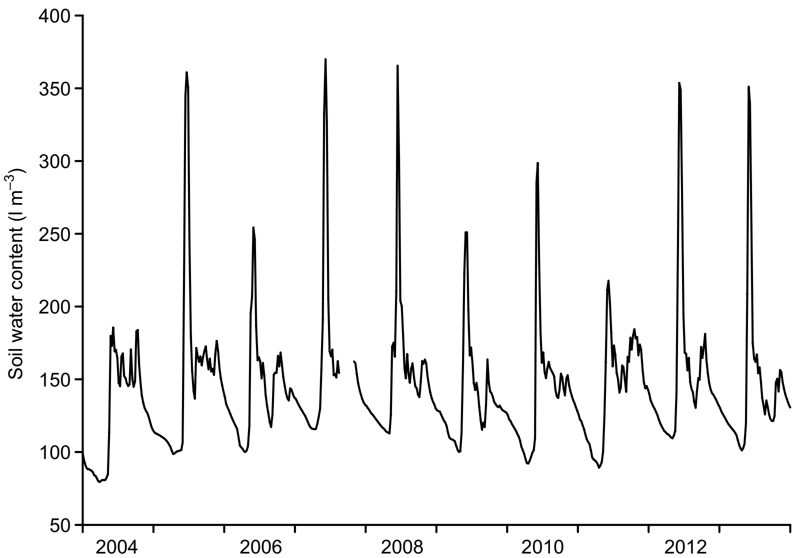

Fig. 3. Long-term changes in the soil water content at the Norway spruce forest station on the northern slope of Sammaltunturi.

(TOC) concentrations are highly variable in the inflow. However, their dynamics are obscured by many interacting in-lake processes, resulting in the smoothed concentrations measured in the (Fig. 4). Both mineralization and sedimentation control in-lake losses of TOC, as they also do in the larger Simojärvi (Lepistö *et al*. 2014).

Greenhouse gas concentrations

Atmospheric concentrations of CO_2 and CH_4 have been measured continuously at Sammaltunturi since 1998 and 2004, respectively (Fig. 5). Marine signals represent the global atmospheric background levels, which were estimated by selecting non-local (consistent, well-mixed) hourly data that correspond to the air mass history above the Atlantic and Arctic Oceans, using a routine described by Aalto *et al*. (2015). As a result, a "Keeling curve" emerges for CO_2, which shows that it is possible to discriminate between different source areas, which are here determined using 5-day reanalysis-driven backward runs of the SILAM dispersion model (Sofiev *et al*. 2006).

The CO_2 and CH_4 data from Sammaltunturi have been actively used in modeling and data-oriented studies that address global and regional GHG sinks and sources, and the transport of GHG emissions in the atmosphere (Aalto *et al*. 2002, 2007, Eneroth *et al*. 2005, Geels *et al*. 2007, Peters *et al*. 2010, Ramonet *et al*. 2010, Chevallier *et al*. 2010, Bergamaschi *et al*. 2015, Tsuruta *et al*. 2015). Owing to the remote location, the tropospheric background data gathered at Sammaltunturi can be used for validation and site inter-comparisons for new monitoring tools, such as those observing total column concentrations at the surface or from space (e.g. Sepúlveda *et al*. 2014, Weaver *et al*. 2014). As the number of atmospheric stations and other monitoring tools has increased considerably during the years that Sammaltunturi has been in operation, the potential for accurately solving regional GHG balances by atmospheric inversion modeling has increased. However, existing background stations are still invaluable in constraining the emission estimates. In addition to CO_2 and CH_4, other long-lived atmospheric trace gases, such as nitrous oxide and hydrogen provide a means to increase the understanding of processes related to climate change. Measurements of these gases at Sammaltunturi have been used in a number of studies addressing surface sinks and sources (Lallo *et al*. 2009, Corazza *et al*. 2011, Yver *et al*. 2011, Thompson *et al*. 2014).

Air quality

FMI started air quality measurements at Sammaltunturi in 1991 and at Matorova in 1995. In gen-

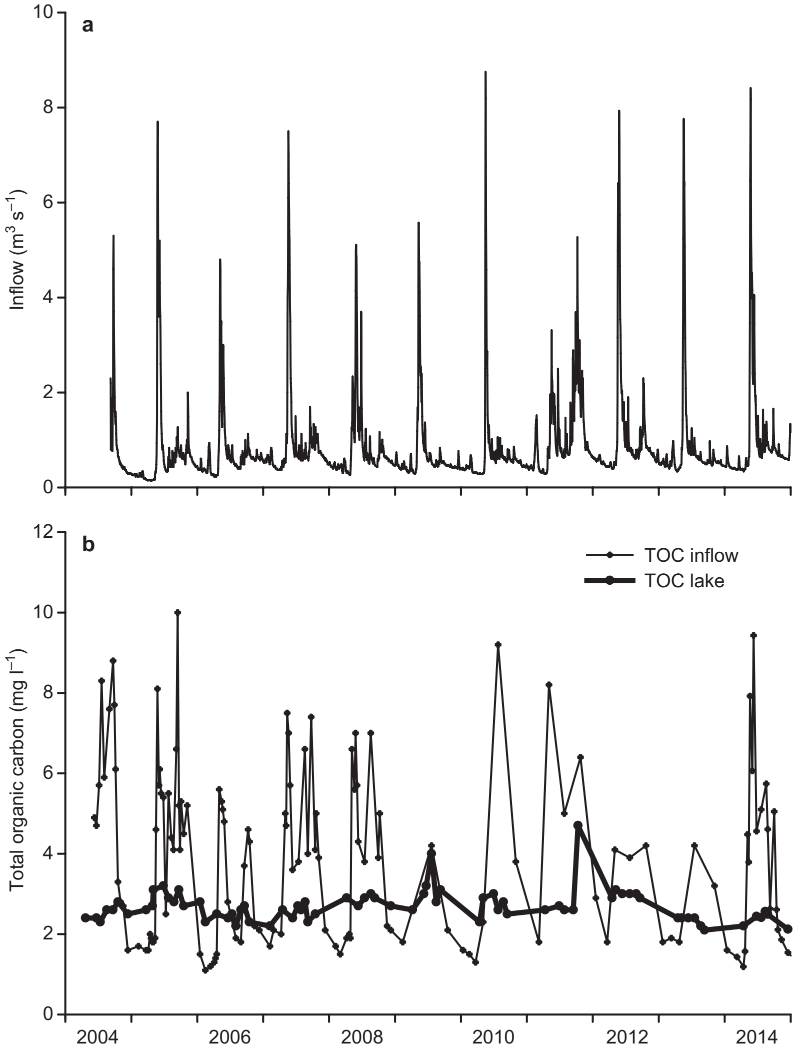

Fig. 4. (**a**) Inflow from the Pyhäjoki and (**b**) total organic carbon (TOC) concentration in the Pyhäjoki and Pallasjärvi.

eral, the air quality at Pallas has improved over the time of the measurements due to decreased emissions in Finland and elsewhere in Europe. For example, there has been a decreasing trend of –3.3% and –2.9% year^{-1} in the atmospheric concentrations of arsenic and nickel, respectively, at Matorova (Fig. 6a and b). For SO_2 and trace elements, the decrease is likely to be due to the decreased emissions from the Kola Peninsula metal industry (about 300 km from Pallas). However, nitrogen compounds have increased and nitrogen deposition at Pallas has been increasing since the mid-1990s (Ruoho-Airola *et al*. 2015), although it is still low compared with those at the other Finnish air quality measurement sites. Further enhancement of the nitrogen load to the ecosystems might be expected as shipping activities are expected to increase in the Arctic in the coming decades (Tuovinen *et al*. 2013). Furthermore, O_3 and non-methane hydrocarbons (NMHC), which react in the air to form O_3, have not decreased since the mid-1990s, although the emissions of NMHC in the European Union have decreased by over 60% in that time (Hellén *et al*. 2015). This may be due to increased concentrations in the air masses arriving from the east.

Even though the Pallas area can, in general terms, be considered a clean environment, the dynamics of the SO_2 concentration measured at Sammaltunturi exhibit wide variation generated

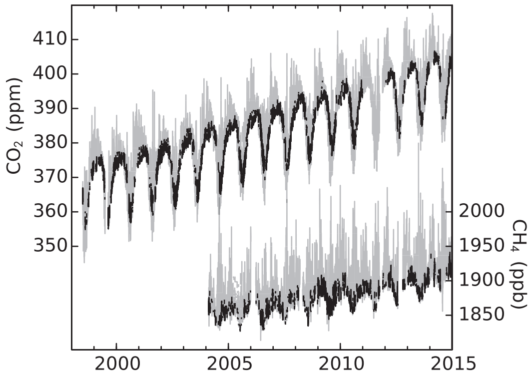

Fig. 5. Hourly concentrations of atmospheric CO_2 (1998–2015) and CH_4 (2004–2015) at Sammaltunturi. Grey lines = all data; black lines = marine signal.

by alternating air masses that pass the station. As SO_2 is a primary pollutant with a short atmospheric lifetime of a day, its atmospheric concentrations largely reflect nearby sources. However, distant emissions can be detected provided the source is sufficiently intense and meteorological conditions are favourable for the transportation of the pollution cloud without excessive dispersion.

The first example of SO_2 measurements depicts hourly data recorded soon after the establishment of the Sammaltunturi station and demonstrates how distinct pollution episodes are superimposed over a low background level (*see* Fig. 7a). During that period, northern Fin-

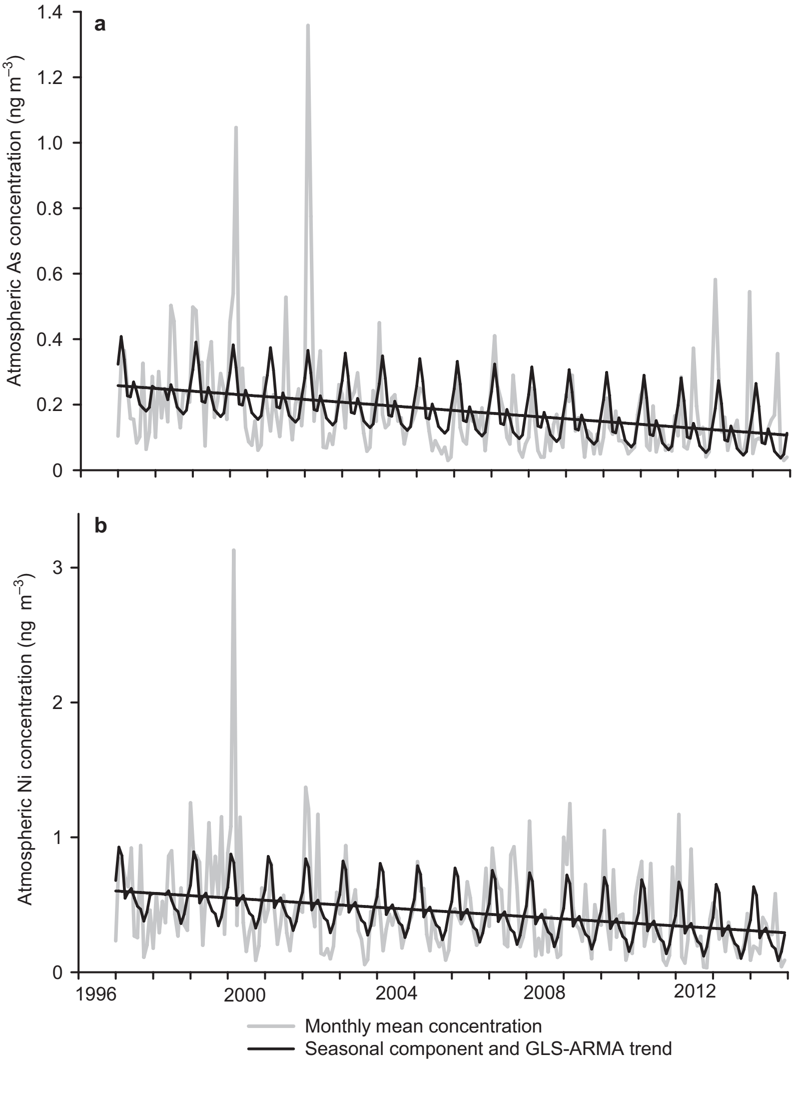

Fig. 6. Atmospheric (**a**) arsenic (As) and (**b**) nickel (Ni) concentrations measured at Matorova in 1996–2013. The trend was calculated by Generalized Least-Squares (GLS) regression with classical decomposition and AutoRegressive Moving Average (ARMA) errors applied for monthly mean values (*see* e.g. Anttila and Tuovinen 2010).

land was frequently exposed to air pollution plumes that mainly originated from the industrial emissions in the Kola Peninsula (Tuovinen *et al*. 1993), evoking environmental concerns (Tikkanen 1995, Tikkanen and Niemelä 1995). Owing to subsequent emission reductions, such pollution episodes have become weaker and less frequent, as the data of November 2013 exemplifies (Fig. 7b).

On 5 September 2014, the SO_2 concentration time series took an anomalous turn (Fig. 7c), when large amounts of the SO_2 emitted by a fissure eruption close to the Bárðarbunga volcano in Iceland (1800 km from Pallas) were transported to northern Finland (Ialongo *et al*. 2015). The highest hourly concentrations produced from this volcanic plume were about 180 μg m^{-3}, which clearly exceeds any previous peaks attributed to anthropogenic emissions. While the concentration gradually decreased, SO_2 of volcanic origin was observed at Pallas throughout that month.

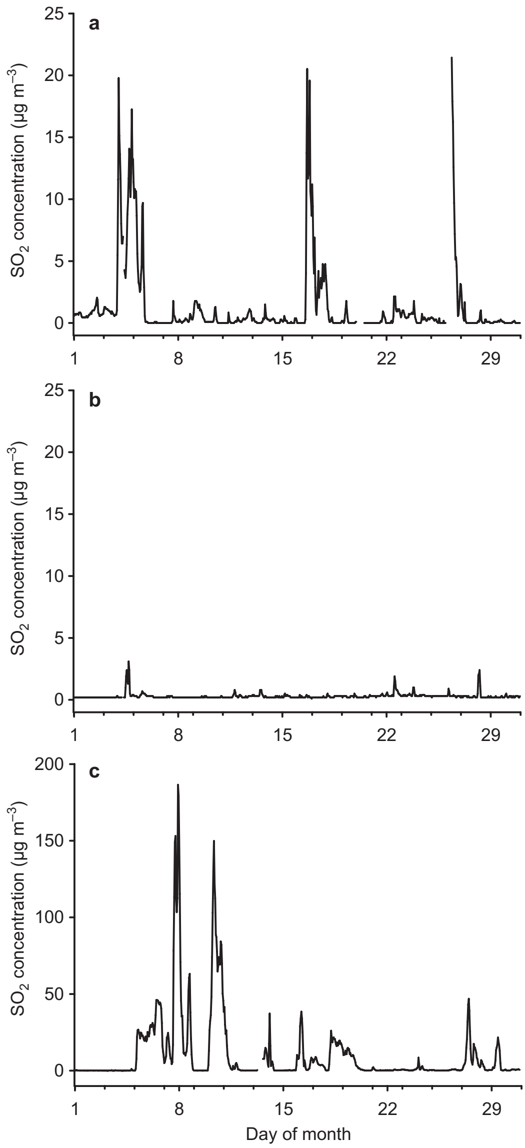

Fig. 7. Sulphur dioxide (SO_2) concentration at Sammaltunturi in (**a**) November 1991, (**b**) November 2013 and (c) September 2014. Note the different concentration scale in **c**.

Aerosol measurements

The first aerosol measurements of total particle number concentrations started at Sammaltunturi in 1996, making them one of the longest time series in the world (Fig. 8). Later, measurements were upgraded to cover a vast variety of aerosol properties: particle number size distributions (in 2000), aerosol scattering coefficients (2000), total air inlet for cloud aerosol studies and aerosol mass (2004), aerosol absorption coefficient (2005, 2007), size distribution of larger particles (2007) and ions (2008), and aerosol hygroscopicity (2008). The Sammaltunturi station is also used to study the microphysical properties of clouds and aerosol cloud activation and chemistry, since it is occasionally inside a cloud.

For almost twenty years, Pallas has served as a unique site for studies of aerosol natural background processes in an environment of minor anthropogenic influences. The process of secondary particle formation and growth to potential cloud condensation nuclei has been extensively studied using measured aerosol size distributions (Komppula *et al*. 2003a, 2003b, Lihavainen *et al*. 2003, Komppula *et al*. 2006, Dal Maso *et al*. 2007, 2008, Asmi *et al*. 2011a). Using Pallas measurements, Kerminen *et al*. (2005) were the first to present solid experimental evidence of the in-cloud activation of these secondary particles, suggesting they hold a significant potential for climate impacts also via clouds. Indeed, the aerosol–cloud interactions, aerosol cloud droplet activation processes and induced direct and indirect climate impacts in Pallas have been

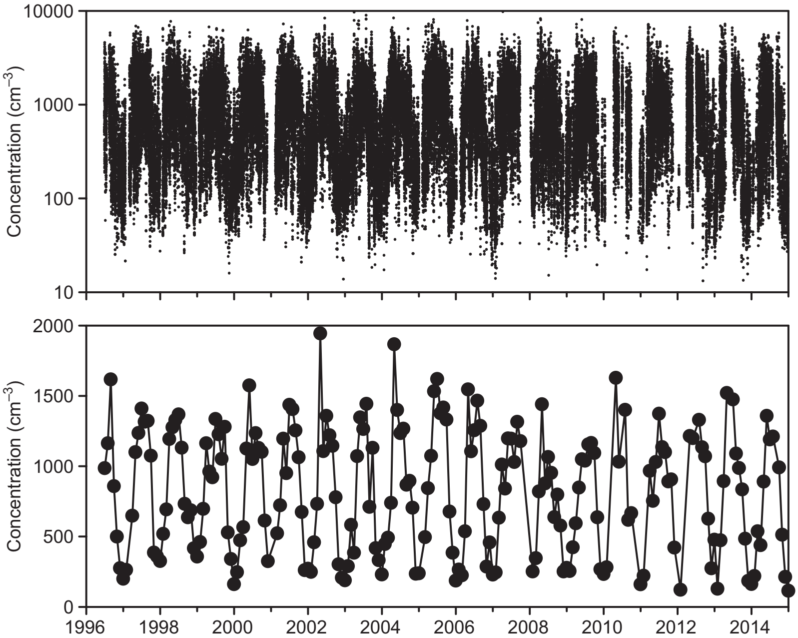

Fig. 8. Time series of aerosol number concentration (> 10 nm) measured at Sammaltunturi. Top and bottom figures show hourly and monthly averages, respectively.

further studied by several groups (Lihavainen *et al*. 2003, Komppula *et al*. 2005, Lihavainen *et al*. 2010). The PaCE (Pallas Cloud Experiment) campaign which will be organized in autumn 2015 is the sixth in series since 2004. The PaCE campaigns focus on resolving the linkages between measured aerosol properties, in-cloud activation and cloud microphysics (Lihavainen *et al*. 2008, Kivekäs *et al*. 2009, Anttila *et al*. 2009, 2012, Jaatinen *et al*. 2014).

Pallas data were also used in source area studies. Tunved *et al*. (2006) showed the high potential of natural emissions from boreal forests for increasing the aerosol mass in Pallas as well. The important role of biogenic emissions for secondary particle formation and growth and for aerosol climate impacts have since been confirmed in several studies (Lihavainen *et al*. 2009, Spracklen *et al*. 2010, Asmi *et al*. 2011a, Scott *et al*. 2014, Hermansson *et al*. 2014). The optical aerosol measurements have provided important knowledge on absorbing aerosol and black carbon concentrations and sources at this gateway to the high Arctic (Hienola *et al*. 2010, Hyvärinen *et al*. 2011, Lihavainen *et al*. 2015). Deposition of these airborne absorbing aerosols into snow pack was studied in Pallas area by Svensson *et al*. (2013) and Forsström *et al*. (2013). The effect of long-range-transported biomass-burning plumes on aerosol properties was also observed at Pallas (Mielonen *et al*. 2013, Targino *et al*. 2013).

Pallas aerosol measurements were part of different-scale integrating studies to understand the complexity and variation of aerosol and cloud condensation nuclei properties (Tunved *et al*. 2003, Laakso *et al*. 2003, Tomasi *et al*. 2007, Kerminen *et al*. 2010, 2012, Kulmala *et al*. 2011, Asmi *et al*. 2013, Collaud Coen *et al*. 2013). The long aerosol data series from Pallas has also enabled aerosol trend studies (Asmi *et al*. 2011b, 2013, Collaud Coen *et al*. 2013, Lihavainen *et al*. 2015), Lagrangian studies on aerosol particle dynamics in the atmosphere (Komppula *et al*. 2006, Kivekäs *et al*. 2009, Väänänen *et al*. 2013, Beddows *et al*. 2014) and parametrization suggestions for climate models (Kivekäs *et al*. 2007, 2008).

Rodent monitoring

Northern Fennoscandia is famous for drastic population cycles of voles and lemmings, which are reflected at trophic levels below and above rodents. Multispecies rodent communities allow

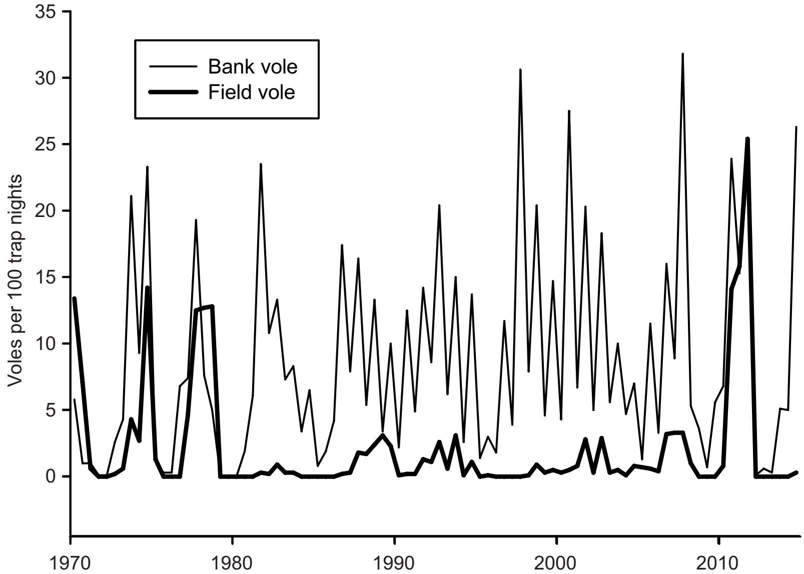

Fig. 9. Population fluctuations of the bank vole (*Myodes glareolus)* and field vole (*Microtus agrestis*) at Pallasjärvi in 1970–2014. The curves are based on two annual samplings, in early June and September, allowing for differentiation of seasonal and multiannual variations.

for the analyses of regulatory factors, either at the whole community or species level. To exemplify: if the population density of many species changes suddenly, it is probable that it can be explained by a single variable at the whole community level, particularly in the case of a collapse in population density. However, if species fluctuate non-synchronously, the regulating factors differ at the species level. Fluctuations of the bank vole (*Myodes glareolus*) and the field vole (*Microtus agrestis*) at Pallasjärvi (Fig. 9), presented here as an example, are characterized by four-year cycles with synchronous peaks and declines in the 1970s, and the nonsynchronous dynamics in the 1980s, 1990s and most of the 2000s. Recently, however, the cyclic pattern seems to have returned.

The research has expanded from original mammalian population ecology to parasite and pathogen dynamics and evolution, for example. Pallasjärvi is currently one of the best-known global rodent research sites. Material from the project have been published in more than 100 peer-reviewed articles and in a host of other publications (for different approaches, *see* e.g. Henttonen 1987, 2000, Henttonen *et al*. 1987, Hanski & Henttonen 1996, 2002, Prévot-Julliard *et al*. 1999, Turchin *et al*. 2000, Yoccoz *et al*. 2001, Haukisalmi *et al*. 2008, 2009, 2010, Razzauti *et al*. 2009, Cornulier *et al*. 2013, Klemme *et al*. 2014).

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[2]Weaver C., Kiemle C., Kawa S.R., Aalto T., Necki J., Steinbacher M., Arduini J., Apadula F., Berkhout H., Hatakka J. & O'Doherty S. 2014. Retrieval of methane source strengths in Europe. *Atmos. Chem. Phys.* 14: 2625–2637.

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Appendix. List of peer-reviewed papers and conference abstracts using data from Pallas area, and topics depicting the content of the papers. [1)] Papers presenting results of studies conducted at Pallas and including the site description; [2)] papers in which the data from the Pallas area were included, but which do not necessarily include the site description.

Reference	Topics
[1]Aalto T.,Hatakka J., Karstens U., Aurela M., Thum T. & Lohila A. 2006. Modeling atmospheric CO_2 concentration profiles and fluxes above sloping terrain at a boreal site. *Atmos. Chem. Phys.* 6: 303–314.	Transport modelling, boundary layer, complex terrain, northern Finland, Pallas region
[2]Abdalla M., Hastings A., Bell M.J., Smith J.U., Richards M., Nilsson M.B., Peichl M., Löfvenius M.O., Lund M., Helfter C., Nemitz E., Sutton M.A., Aurela M., Lohila A., Laurila T., Dolman A.J., Belelli-Marchesini L., Pogson M., Jones E., Drewer J., Drösler M. & Smith P. 2014. Simulation of CO_2 and attribution analysis at six European peatland sites using the ECOSSE model. *Water Air Soil Poll.* 225: 2182, doi: 10.1007/s11270-014-2182-8.	Heterotrophic respiration, modelling, wetlands, management, carbon emissions
[2]Derome J., Lindroos A.-J. & Lindgren M. 2001. Soil acidity parameters and defoliation degree in six Norway spruce stands in Finland. *Water, Air Soil Poll.: Focus* 1: 169–186.	Soil pH, base saturation, exchangeable Al, stand condition
[2]Drewer J., Lohila A., Aurela M., Laurila T., Minkkinen K., Penttilä T., Dinsmore K.J., McKenzie R., Helfter C., Flechard C., Sutton M.A. & Skiba U.M. 2010. Comparison of greenhouse gas fluxes and nitrogen budgets from an ombrotrophic bog in Scotland and a minerotrophic sedge fen in Finland. *Eur. J. Soil Sci.* 61: 640–650.	Carbon dioxide, methane, nitrous oxide, nitrogen flux, Global Warming Potential
[2]Flechard C.R., Nemitz E., Smith R.I., Fowler D., Vermeulen A.T., Bleeker A., Erisman J.W., Simpson D., Zhang L., Tang Y.S. & Sutton M.A. 2011. Dry deposition of reactive nitrogen to European ecosystems: a comparison of inferential models across the NitroEurope network. *Atmos. Chem. Phys.* 11: 2703–2728.	Atmospheric chemistry, NH_3, NO_2, HNO_3, HONO, non-stomatal pathway
[1]Hakola H., Hellén H. & Laurila T. 2006. Ten years of light hydrocarbon (C_2–C_6) concentration measurements in background air in Finland. *Atmos. Environ.* 40: 3621–3630.	GAW station, canister samples, seasonal variation, natural emissions
[1]Hatakka J., Viisanen Y. & Plathan P. 1997. Pallas–Sodankylä, a global atmosphere watch station. In: Lovén L. & Salmela S. (eds.), *Pallas-symposium 1996*, Research Papers 623, Finnish Forest Research Institute, Rovaniemi, pp. 13–16.	Atmospheric research, GAW station, long-term monitoring
[2]Helmisaari H.-S., Derome J., Nöjd P. & Kukkola M. 2007. Fine root biomass in relation to site and stand characteristics in Norway spruce and Scots pine stands. *Tree Physiol.* 27: 1493–1504.	Boreal forests, carbon allocation, understory vegetation
[2]Hilli S., Stark S. & Derome J. 2008. Carbon quality and stocks in organic horizons in boreal forest soils. *Ecosystems* 11: 270–282.	Decomposition, sequential fractionation, climatic gradient
[2]Hilli S., Stark S. & Derome J. 2008. Qualitative and quantitative changes in water-extractable organic compounds in the organic horizon of boreal coniferous forests. *Boreal Env. Res.* 13 (suppl. B): 107–119.	Decomposition gradient, carbon, nitrogen, climatic zones
[2]Hilli S., Stark S. & Derome J. 2008. Water-extractable organic compounds in different components of the litter layer of boreal coniferous forest soils along a climatic gradient. *Boreal Env. Res.* 13B: 92–106.	Tree, dwarf shrub, moss, carbon, nitrogen
[1]Holmén K. & Paatero J. (eds.) 2008. *The Second Ny-Ålesund–Pallas-Sodankylä Atmospheric Research Workshop*, *Ny-Ålesund, Svalbard, Norway 16–18 April 2007*, *Extended Abstracts*. Brief Report Series No. 08, Norwegian Polar Institute, Tromsö.	Atmospheric research, GAW station, long-term monitoring
[2]Hope A.G., Waltari E., Dokuchaev N.E., Abramov S., Dupal T., Tsvetkova A., Henttonen H., MacDonald S.O. & Cook J.A. 2010. High latitude diversification within Eurasian least shrews and Alaska tiny shrews. *J. Mammal.* 91: 1041–1057.	Geologic event, genetic variability, phylogeographic break

[1]Huhta E. & Sulkava P. 2014. The impact of nature-based tourism on bird communities: a case study in Pallas-Yllästunturi National Park. *Environ. Manage*. 53: 1005–1014.
Disturbance, bird communities, nature-based tourism, recreation

[2]Laurila T. & Hakola H. 1996. Seasonal cycle of C_2–C_5 hydrocarbons over the Baltic Sea and northern Finland. *Atmos. Environ.* 30: 1597–1607.
Ambient air, seasonal cycle, photochemical transformation, ozone

[1]Laurila T., Tuovinen J.-P. & Hatakka J. 2009. Ozone concentration variations observed in northern Finland in relation to photochemical, transport and cloud processes. *Boreal Env. Res.* 14: 550–558.
GAW station, trajectories, source area, nitrogen oxides

[2]Lavikainen A., Haukisalmi V., Lehtinen M.J., Henttonen H., Oksanen A. & Meri S. 2008. Phylogeny of the family Taeniidae based on the mitochondrial *cox1* and *nad1* genes. *Parasitology* 135: 1457–67.
DNA sequencing, phylogenetic relationship, cryptic sister species

[2]Leppelt T., Dechow R., Gebbert S., Freibauer A., Lohila A., Augustin J., Drösler M., Fiedler S., Glatzel S., Höper H., Järveoja J., Lærke P.E., Maljanen M., Mander Ü., Mäkiranta P., Minkkinen K., Ojanen P., Regina K. & Strömgren M. 2014. Nitrous oxide emission budgets and land-use-driven hotspots for organic soils in Europe. *Biogeosci*. 11: 6595–6612.
Greenhouse gases, fuzzy modelling, peatland management, upscaling

[2]Metzger C., Jansson P.-E., Lohila A., Aurela M., Eickenscheidt T., Belelli-Marchesini L., Dinsmore K., Drewer J., van Huissteden J. & Drösler M. 2015. CO_2 flux and ecosystem dynamics at five European treeless peatlands — merging data and process oriented modelling. *Biogeosci.* 12: 125–146.
Process modelling, climate gradient, land use, heterotrophic respiration

[2]Mustajärvi K., Merilä P., Derome J., Lindroos A.-J., Helmisaari H.-S., Nöjd P. & Ukonmaanaho L. 2008. Fluxes of dissolved organic and inorganic nitrogen in relation to stand characteristics and latitude in Scots pine and Norway spruce stands in Finland. *Boreal Env. Res*. 13 (suppl. B): 3–21.
Dissolved nitrogen, throughfall, percolation water, bulk deposition

[1]Paatero J. 2000. Wet deposition of radon-222 progeny in northern Finland measured with an automatic precipitation gamma analyser. *Radiat. Prot. Dosim*. 87: 273–280.
Wet deposition, radon-222 progeny, washout

[1]Paatero J. & Holmén K. (eds.) 2004. *The First Ny-Ålesund–Pallas-Sodankylä Atmospheric Research Workshop*, *Pallas, Finland 1–3 March 2004, Extended Abstracts*. Finnish Meteorological Institute Reports 2004:7, Helsinki.
Atmospheric research, GAW station, long-term monitoring

[2]Paatero J., Vaaramaa K., Buyukay M., Hatakka J. & Lehto J. 2015. Deposition of atmospheric ^{210}Pb and total beta activity in Finland. *J. Radioanal. Nucl. Chem*. 303: 2413–2420.
Lead-210, deposition, specific activity

[2]Petrescu A.M.R., Lohila A., Tuovinen J.-P., Baldocchi D.D., Desai A.R., Roulet N.T., Vesala T., Dolman A.J., Oechel W.C., Marcolla B., Friborg T., Rinne J., Matthes J.H., Merbold L., Meijide A., Kiely G., Sottocornola M., Sachs T., Zona D., Varlagin A., Lai D.Y.F., Veenendaal E., Parmentier F.-J.W., Skiba U., Lund M., Hensen A., van Huissteden J., Flanagan L.B., Shurpali N.J., Grünwald T., Humphreys E.R., Jackowicz-Korczyński M., Aurela M.A., Laurila T., Grüning C., Corradi C.A.R., Schrier-Uijl A.P., Christensen T.R., Tamstorf M.P., Mastepanov M., Martikainen P.J., Verma S.B., Bernhofer C. & Cescatti A. 2015. Uncertain climate footprint of wetlands under human pressure. *PNAS* 112: 4594–4599.
CH_4 flux, CO_2 flux, eddy covariance, radiative forcing, peatland management

[2]Pudas E., Tolvanen A., Poikolainen J., Sukuvaara T. & Kubin E. 2008. Timing of plant phenophases in Finnish Lapland in 1997–2006. *Boreal Env. Res.* 13: 31–43.
Phenological Network, climatic conditions, temperature sum, snow melt day

[2]Salemaa M., Derome J. & Nöjd P. 2008. Response of boreal forest vegetation to the fertility status of the organic layer along a climatic gradient. *Boreal Env. Res.* 13 (suppl. B): 48–66.
Understorey vegetation, stand productivity, climatic factors, nitrogen

[2]Sippola A.-L., Siitonen J. & Kallio R. 1998. Amount and quality of coarse woody debris in natural and managed coniferous forests near the timberline in Finnish Lapland. *Scand. J. For. Res.* 13: 204–214.
Biodiversity, coarse woody debris (CWD), timberline forests

[2]Skiba U., Drewer J., Tang Y.S., van Dijk N., Helfter C., Nemitz E., Famulari D., Cape J.N., Jones S.K., Twigg M., Pihlatie M., Vesala T., Larsen K.S., Carter M.S., Ambus P., Ibrom A., Beier C., Hensen A., Frumau A., Erisman J.W., Brueggemann N., Gasche R., Butterbach-Bahl K., Neftel A., Spirig C., Horvath L., Freibauer A., Cellier P., Laville P., Loubet B., Magliulo E., Bertolini T., Seufert G., Andersson M., Manca G., Laurila T., Aurela M., Lohila A., Zechmeister-Boltenstern S., Kitzler B., Schaufler G., Siemens J., Kindler R., Flechard C. & Sutton M.A. 2009. Biosphere–atmosphere exchange of reactive nitrogen and greenhouse gases at the NitroEurope core flux measurement sites: measurement strategy and first data sets. *Agric. Ecos. Environ.* 133: 139–149.
Nitrogen cycle, reactive N measurements, modelling, network

[2]Thompson R.L., Ishijima K., Saikawa E., Corazza M., Karstens U., Patra P.K., Bergamaschi P., Chevallier F., Dlugokencky E., Prinn R.G., Weiss R.F., O'Doherty S., Krummel P., Steele L.P., Fraser P., Vermeulen A., Tohjima Y., Jordan A., Haszpra L., Steinbacher M., Van der Laan S., Aalto T., Meinhardt F., Popa M.E., Moncrieff J. & Bousquet P. 2014. TransCom N_2O model inter-comparison — Part II: Atmospheric inversion estimates of N_2O emissions. *Atmos. Chem. Phys*. 14: 6177–6194.
Tropospheric nitrous oxide concentrations, atmospheric chemistry transport modelling, data assimilation

[2]Ylisirniö A.-L., Berglund H., Aakala T., Kuuluvainen T., Kuparinen A-M., Norokorpi Y., Hallikainen V., Mikkola K. & Huhta E. 2009. Spatial distribution of dead wood and the occurrence of five saproxylic fungi in old-growth timberline spruce forests in northern Finland. *Scand. J. Forest Res.* 24: 527–540.
Biodiversity management, boreal forests, coarse woody debris, polyporous fungi