

How is our forest?

34 years of forest observation

Intercantonal Permanent Forest Observation Program of the Cantons AG, BE, BL, BS, GR, SO, TG, ZG, ZH, of the Environmental offices of Central Switzerland and of the Federal Office for the Environment (FOEN) Results from 2013 to 2017 | Report 5



UMWELTFACHSTELLEN

German report with English introduction



INSTITUT FÜR ANGEWANDTE PFLANZENBIOLOGIE SCHÖNENBUCH

Impressum

Eine Information der kantonalen Forstämter Aargau, Bern, Basellandschaft, Basel-Stadt, Graubünden, Solothurn, Thurgau, Zug und Zürich und der Umweltfachstellen der Zentralschweiz mit Unterstützung des Bundesamtes für Umwelt (BAFU).

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Diese Studie wurde im Auftrag der Kantone AG, BE, BL, BS, GR, SO, TG, ZG, ZH, der Zentralschweizer Kantone und des BAFU verfasst. Für den Inhalt ist allein der Auftragnehmer verantwortlich.

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How is our forest?

Design | Herstellung

krause-graphics.com | Lörrach

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34 Jahre Walddauerbeobachtung

Interkantoniales Walddauerbeobachtungsprogramm im Auftrag der Kantone AG, BE, BL, BS, GR, SO, TG, ZG, ZH und der Zentralschweizer Kantone mit Beteiligung des BAFU | Bericht 2013-2017

Programme d'observation permanente intercantonal des forêts des cantons d'AG, BE, BL, BS, GR, SO, TG, ZG, ZH, des offices de l'environnement de la Suisse centrale et de l'OFEV

Résultats de 2013 à 2017 | Rapport 5

Programma intercantonale di monitoraggio permanente dei boschi nei Cantoni di AG, BE, BL, BS, GR, SO, TG, ZG, ZH e degli uffici per l'ambiente della Svizzera Centrale con la partecipazione dell'UFAM.

Risultati dal 2013 al 2017 | Rapporto 5

Intercantonal Permanent Forest Observation Program of the Cantons AG, BE, BL, BS, GR, SO, TG, ZG, ZH, of the environmental offices of Central Switzerland and of the Federal Office for the Environment (FOEN)

Results from 2013 to 2017 | Report 5



Schönenbuch, Januar 2018

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Main results from 34 years of permanent forest monitoring

Key messages:

- Phosphorus nutrition in European beech and Norway spruce has declined by 25% and 15%, respectively, leading to severe deficiency.
- Since 1987, stem growth of European beech has declined by 31% while there is no clear trend in Norway spruce.
- Nitrogen deposition >25 kg ha⁻¹ yr⁻¹ inhibits growth of European beech and Norway spruce.
- Increased nitrogen deposition exacerbates the effect of drought on stem growth of European beech and the mortality of Norway spruce.
- Interactions between increased nitrogen deposition, extreme drought events and warmer winters explain a large part of the growth reductions in European beech.
- Increased nitrogen deposition reduces mycorrhization of roots and the diversity of ectomycorrhiza in European beech, while base saturation is significantly shaping the composition of ectomycorrhizal communities.
- Since 2000, the fructification of European beech has strongly increased.
- Soil acidification has increased during the 34 years of monitoring.
- Wind throw risk is clearly higher on soils with low base saturation.
- Although ash dieback has spread across the whole country since 2008, we still observe non-infested trees.
- Crown transparency in oaks does not respond to drought like in European beech and Norway spruce.
- With regard to nutrient balance, whole tree harvesting is not sustainable, especially not under current nitrogen deposition levels.



Photo 1: Drought damages in downy oak forests around La Sarraz (VD). Photo taken on July 29th 2015.

Permanent forest monitoring is a valuable tool to observe and document gradual changes in forest ecosystems. In the 1980s, at the beginning of the monitoring programme, the focus was on the effects of acid rain and ozone. Later also nitrogen deposition and soil

acidification became important issues. The latest developments in Swiss forests suggest an increasing significance of climate change for forest health. The observed trends are therefore the result of combined anthropogenic stress factors. In this first chapter, we briefly present the main results and conclusions from 34 years of permanent forest monitoring and give reference to subsequent chapters where the results are more described in detail (in German only).

During the last four years of the forest monitoring, progressing climate change primarily attracted our attention. During the long **drought** period in summer 2015, trees in several regions turned brown including downy oak forests (*Quercus pubescens* Willd.) in the canton Valais and on the Central

plateau, for example in La Sarraz VD (Photo 1). Late frosts, warm winters, intense fructification events, high ozone concentrations and drought play a major role for crown transparency of European beech and Norway spruce, while the crown transparency of oak is not affected by drought (Chap. 10). The development of crown transparency in European beech (*Fa-*

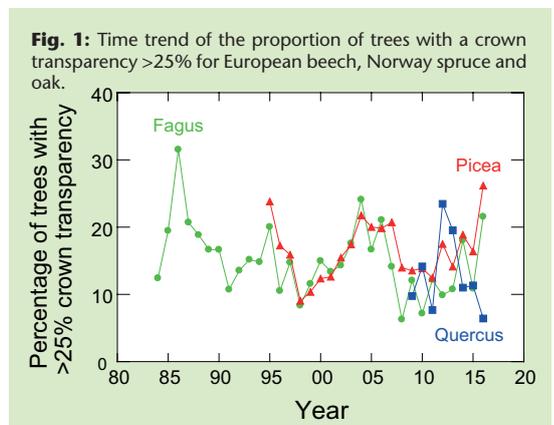


Fig. 1: Time trend of the proportion of trees with a crown transparency >25% for European beech, Norway spruce and oak.

gus sylvatica L.) and Norway spruce (*Picea abies* (L.) H. Karst.) over time shows a rather synchronous pattern while the trend of oaks (*Quercus robur* L., *Quercus petraea* Liebl., *Quercus pubescens* Willd.) is rather opposing (Fig.



Photo 2: European beech with intense fructification.

1, Chap. 2.1). The strong discolouration observed in shoots harvested from the beech crowns during August 2015 is most likely also an effect of heat and drought.

In European beech, fructification has intensified during the last 30 years in both frequency and quantity (Chap. 4.2). In forest literature, masting events are defined when fruit numbers exceed 150 fruits per square meter ground surface. So far, the most intense fructification occurred in 2011, with an average of 430 fruits per square meter. In 2014, we counted 360 fruits per square meter. Another year with a very intense fructification was 2016, when the crowns turned brown because of small leaves and nu-

merous fruits (Photo 2). We will have more quantitative information on the 2016 fructification after the next shoot harvest in 2019 when we will count the annual fruit scars backwards. This trend in fructification has a negative effect on tree growth as it consumes essential resources.

When Norway spruce trees die this is usually linked to an infestation by **bark beetles**. These beetles preferably attack weakened trees like those stressed by heat and drought. During the long drought periods in the summers of 2015 and 2016, bark



Photo 3: Bark beetle infestation in Scheidwald (BE).

beetles found favourable conditions and therefore, in 2017, the degree of infestation reached the second highest value since the beginning of the monitoring programme. Our data also show that the effect of drought stress on infestation is greatly enhanced by high nitrogen deposition or nutrient deficiencies (potassium, magnesium; Chap. 2.2.2). This indicates that a

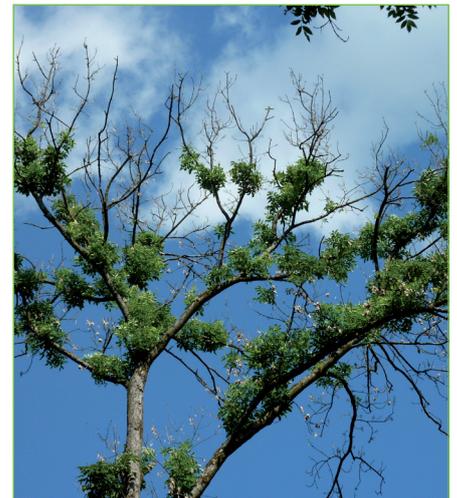


Photo 4: Infested ash tree

combination of climate stress and pollution has a greater effect on trees. For European beech mortality is increased by drought stress or phosphorus deficiency (Chap. 2.2.1).

Ash dieback is caused by a fungus originating in Asia and was first observed in the 1990s in Lithuania and Poland from where it spread rapidly across Europe (1). In Switzerland the first symptoms were registered in 2008 in the Northwest from where it spread across the whole country within seven years (2, Photo 4). In 2013, the IAP started a monitoring project to investigate the course of the disease and to identify resistant trees. From a total of 204 selected trees, 22% were visually classified to be free of symptoms in 2017 (Chap. 2.3).

Since the 1990s, apart from the gales Vivian in 1990 and Lothar in 1999, storm damages have increased (Chap. 2.2.4). Previous data analyses also showed that trees are uprooted more

frequently on sites with acidic soils. High nitrogen deposition loads also impair the root system and trees are prone to be uprooted more easily as for example in Giswil OW (Photo 5).

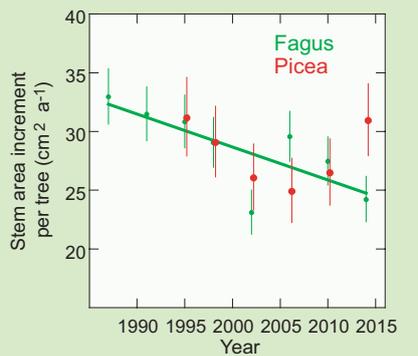
The stem increment has declined clearly for European beech since 1987 (Fig. 2, Chap. 5.1). For Norway spruce, a decline has been observed until 2006 and the increment has increased again thereafter. On sites with both oak and European beech, relative average growth of oak is lower than for beech.

Photo 5: Storm damages in Giswil (OW).



While storm damages, fructification or crown discoloration after long drought periods are clearly visible phenomena, changes in health or nutrient status of trees (Chap. 2.1 and 3, respectively), in stem increment (Chap 5.1) and soil processes (Chap 7.2) can only be established with standardized methods and repeated assessments. Therefore, long term forest monitoring of a large number of trees (Fig. 3) is a perfect in-

Fig. 2: Time trends of basal area increments per tree for European beech and Norway spruce.



strument to investigate natural forest development, to recognize temporal and spatial changes in forest ecosystems and to disentangle the contribution of the different factors leading to the observed changes.

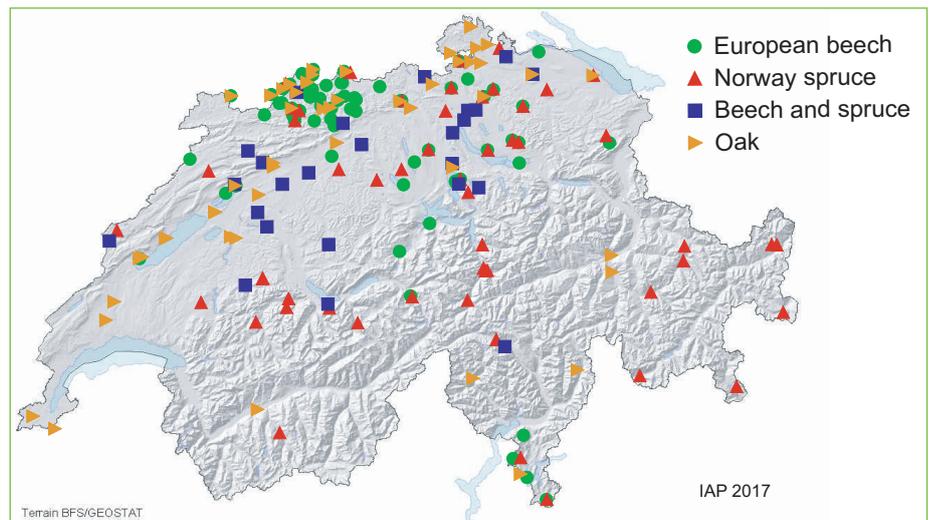
Climate change

The intergovernmental Panel on Climate Change (IPCC) has documented the influence of human activities on the environment (3). In Switzerland, temperatures have already increased

by 1.8°C since 1864 (4). There are no trends in precipitation but higher temperatures enhance evapotranspiration and drought stress in forest ecosystems. Moreover, the frequency of long-term drought and heat waves has clearly increased during the last decades.

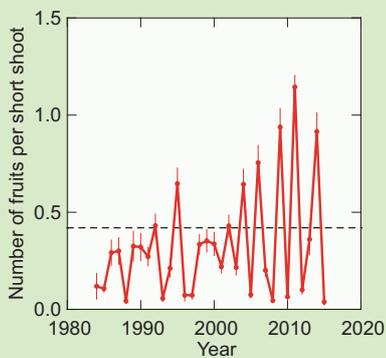
The permanent forest observation plots cover a quite large temperature and humidity gradient and are therefore ideally suited to analyse climate effects on forests. According to our evaluation, increased temperatures alone have a minor effect on forest trees, except for warmer winter temperatures (increased average temperatures from December to March) which are negatively related with stem increment in Norway spruce. This effect is aggravated by high nitrogen loads. For European beech, warmer winter temperatures restrain stem increments only in plots with a nitrogen deposition or with an inadequate magnesium supply (Chap. 5.2). Increasing temper-

Fig. 3: Permanent forest observation plots of the IAP.



ature (5) and vapour pressure deficit also play a role for beech fructification which has increased both in intensity and frequency during the last decades (Chap. 4.2). Because higher fructification has a negative influence on stem increments and is positively correlated

Fig. 4: Time trend of fructification in European beech. The dashed line shows the threshold for a mast fruiting event (150 fruits/m²). Vertical bars indicate 95% confidence intervals.



with crown transparency, beech trees cannot profit from increased temperatures and their vitality may even be reduced.

The effect of drought on stem increment is relevant for forestry, but the underlying processes not well understood (6). Analyses based on our permanent measurements show that the drought effect on stem increment is best explained by site water balance which is the cumulated difference between the sum of precipitation and soil water storage capacity on the one hand and the potential evapotranspiration on the other hand.

For European beech, stem increment is clearly more sensitive against drought in plots with high nitrogen deposition

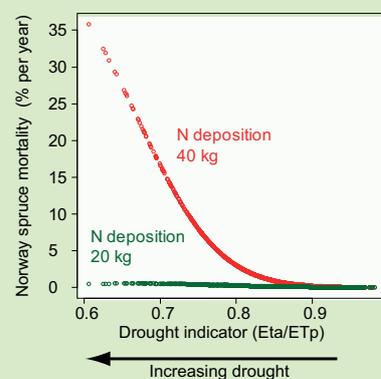
or inadequate potassium supply. These interactions between climate change and nitrogen pollution probably explain the observed growth reductions in European beech.

Acute drought stress causes a negative pressure within the xylem leading to air bubbles. This effect impairs the water conductance of plants and is called embolism or cavitation. Drought tolerance of various tree species depends on whether this process occurs already under ambient conditions or whether there is a safety range (7, 8). A tree dies when a certain proportion of the xylem has lost its function (9). By closing its stomata, a tree can counteract such a drought stress. Our analyses of carbon and oxygen isotopes in stem discs suggest that this process is more efficient in European beech than in Norway spruce (Chap. 10.4). Another option to avoid drought stress is the uptake of water from deeper soil layers. This has been investigated with carbon and oxygen isotope analyses in rainwater, soil, branches and leaves (Chap. 10.5). Our collaboration with the Paul Scherrer institute (PSI) suggests that Norway spruce take up water rather from the upper soil layers, while the water uptake of European beech and oak occurs in deeper soil layers. Additionally, we were able to demonstrate the significance of deep soil layers during extreme drought for oak forests in Möhlin AG. During the long drought period in summer 2015, the stem water tension was clearly enhanced. Although soil water sensors down to 60cm depth did not detect any plant available water, there was still wa-

ter flux within the xylem. When these deeper soil layers do not exist, even downy oak forests may develop significant drought damages as in La Sarraz VD (Photo 1).

According to our results, mortality of adult trees in temperate regions is not directly affected by hydraulic failure of the xylem during drought stress. More probably, trees with a reduced vitality due to drought stress are more easily attacked by secondary parasites like bark beetles, honey fungus or beech bark disease. Our conclusion is based on the fact that most dying trees show reduced vitality for several years preceding death. In all three tree species drought has to be averaged over several years to predict mortality (Chap. 2.2). The best indicator for drought-induced mortality was the ratio between actual and potential evapotranspiration (Chap.10.3). This ratio is calculated based on hydrological models and indicates how much evapotranspiration is limited by drought. The effect of drought on the mortality rate of Norway spruce is enhanced by

Fig. 5: Interactions between drought and nitrogen deposition on mortality in Norway spruce. Predictions from a multivariate regression setting all other parameters at their mean.



high nitrogen deposition and nutrient imbalances (Fig. 5; Chap. 2.2).

As a consequence of climate change, bud burst of European beech has shifted forward to earlier dates in spring (Chap. 11.2). Also due to drought, foliage discoloration starts earlier. Accordingly, the vegetation period has prolonged by 10 days between 1980 and 2015.

Nitrogen deposition

Agriculture, traffic and industry are emitting large amounts of reactive nitrogen compounds which are deposited into ecosystems as rain (wet deposition), aerosols or gas (dry deposition). Because of their high surface roughness, forests are an efficient sink for these compounds. Depositions in Switzerland can rise to more than 50 kg nitrogen per hectare and year ($\text{kg N ha}^{-1} \text{a}^{-1}$). The sensitivity of forest ecosystems to increased nitrogen depositions has already been recognised in the 1980s (10, 11). The UNECE convention on long-range transboundary air pollution (CLRTAP) has established Critical Loads for nitrogen for various ecosystems (12). For temperate deciduous forests the Critical Loads were set to $10\text{-}20 \text{ kg N ha}^{-1} \text{a}^{-1}$ and for coniferous forests to $5\text{-}15 \text{ kg N ha}^{-1} \text{a}^{-1}$. These Critical Loads are exceeded in 95% of the Swiss forests (13).

Due to air quality control measures, nitrogen deposition has slightly decreased in recent years. But through-fall measurements do not necessarily reflect this trend. For example in Muri AG, deposition remained stable, and in Brislach BL it even increased. In Sagno TI, deposition was reduced between

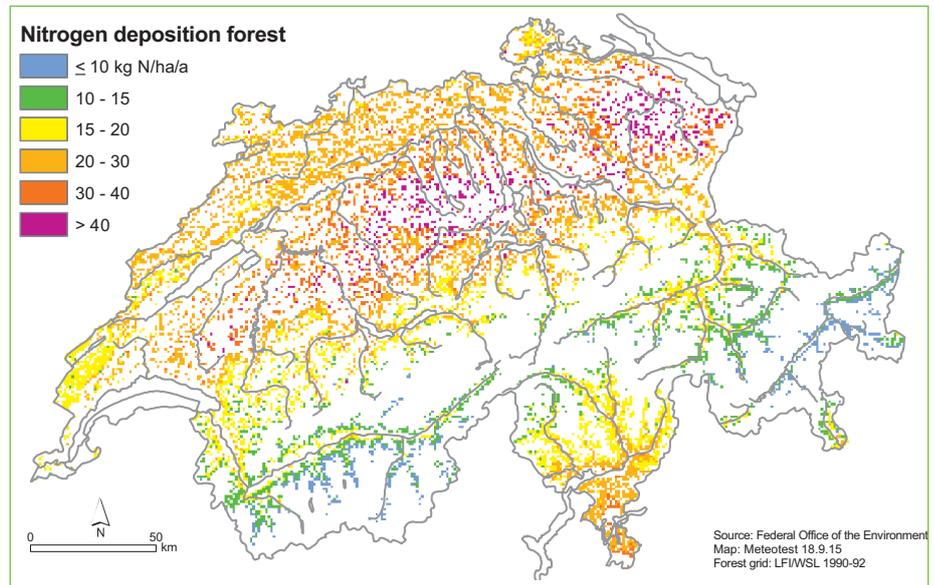


Fig. 6: Map of modelled nitrogen deposition into forests in 2010 (BAFU/Meteotest).

2003 and 2006, but increased again between 2006 and 2015. In spite of the decrease, nitrogen pollution stays too high.

Nitrogen is an essential nutrient for plants enhancing growth. Since the 1980s, an increased forest growth in Europe has been reported (14) which has been attributed to nitrogen deposition. A growth increase is, however, only possible when all other essential elements like phosphorus, potassium and magnesium are sufficient. The growth increase by nitrogen is therefore limited and dependent on nutrient reserves in the forest soil and nutrient uptake capacity. This is mirrored in our monitoring data: Nitrogen deposition below $25 \text{ kg N ha}^{-1} \text{a}^{-1}$ slightly stimulates growth (Abb. 7, Chap. 5.1). At higher deposition loads, Norway spruce shows a slight and European beech a massive growth reduction (Chap. 5.2). Changes in nutrient levels in trees

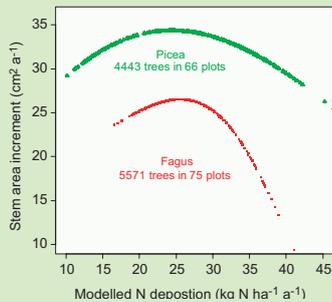
and interactions between the nitrogen pollution and climate change play a major role for this effect. High nitrogen loads and the associated nutrient imbalances are amplifying the drought effects and inducing a negative relation between winter temperature and stem increment of European beech (Chap. 5.2). These interactions are most probably responsible for the growth reductions in European beech we are observing.

Photo 6: Manure spreading with a pressure vessel increases nitrogen pollution.



Another effect of increased nitrogen deposition is an unbalanced nutrition of trees. The decline of foliar phosphorus which has been observed in all three tree species is suggested to be a consequence of excess nitrogen. In European beech this is also the case for foliar potassium and magnesium

Fig. 7: Relationship between stem increment of European beech and Norway spruce and nitrogen deposition. For this figure, all other predictors except nitrogen deposition were averaged (15).



(Chap. 3). Today, foliar concentrations of phosphorus in both Norway spruce and European beech as well as of potassium and magnesium in European beech are at extremely deficient levels (Chap. 3; Fig. 8). Concentration ratios of nitrogen to phosphorus in European beech and Norway spruce are far above thresholds for harmonious nutrition and are related to nitrogen deposition.

Photo 7: Stem increment measurement with a caliper.

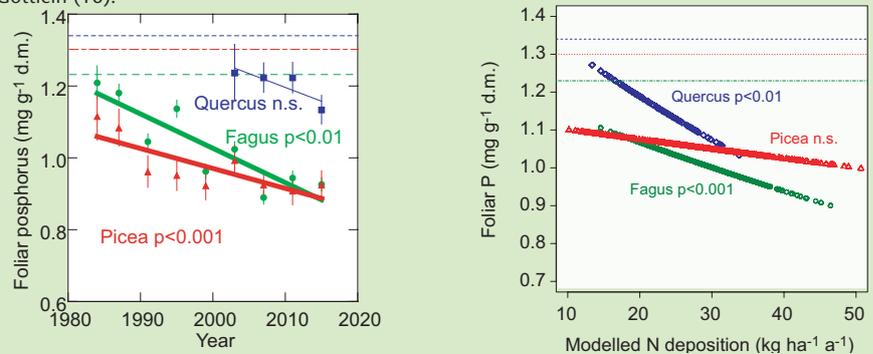


Our data also suggest that the uptake of phosphorus and potassium in beech of phosphorus from the soil is impaired at high nitrogen deposition loads. Nutrition of oak in general is closer to optimum levels.

The nutrient imbalances in trees may give rise to a reduced resistance towards parasites and drought stress. In Norway spruce, mortality under drought stress is enhanced when either nitrogen deposition is high or there is an imbalance in foliar potassium and magnesium (Chap. 2.2.2). For European beech, mortality is increased by phosphorus deficiency (Chap. 2.2.1).

Nitrogen pollution is causing changes in forest ground vegetation and soil microbes. Nitrogen sensitive, usually endangered plant species disappear, while nitrophilic species like nettles or elder become more frequent. Blackberry cover increases exponentially when nitrogen deposition is above 20-25 kg N ha⁻¹ a⁻¹ (Fig. 10). Mycorrhizal diversity on roots of European beech is reduced on plots with high nitrogen deposition (18; Chap. 10, Fig. 11). Root colonization of ectomycorrhiza is reduced. Interestingly, ectomycorrhizal species that play an important role for phosphorus uptake of trees get rarer on plots with increased nitrogen deposition.

Fig. 8: Development of phosphorus concentrations in foliage of European beech, Norway spruce and oak (left) and the relationship between foliar phosphorus concentrations and modelled nitrogen deposition (right). Dashed lines indicate thresholds for adequate nutrition according to Göttlein (16).



Nitrogen not being absorbed from the soil by vegetation and microbes is leached as nitrate. This process is an indicator of excess nitrogen. Thresholds for nitrate leaching defined in the framework of the CLRTAP (17) are differentiated within Switzerland with respect to elevation. These thresholds are surpassed in about half of our forest plots equipped with lysimeters for soil solution analysis (Fig. 9), although there has been a slight decrease in nitrate leaching since 2005.

Soil acidification

As a consequence of air quality control measures, deposition of sulphur compounds, also known as acid rain, have strongly declined. Nitrogen deposition is, however, still high enough to cause significant acidification. In soil, ammonium is transformed to nitrate, releasing acidity. Nitrate not taken up by plants or microorganisms is leached, carrying along positive ions. These include the base cations calcium, potassium, magnesium and sodium, at

low pH levels also manganese and aluminium (Fig. 12). As a result, the base saturation of the soil cation exchangers decreases. Moreover, the ratio between cations and aluminium in soil solution, the so-called BC/Al-ratio, drops. Altogether, this process is called soil acidification.

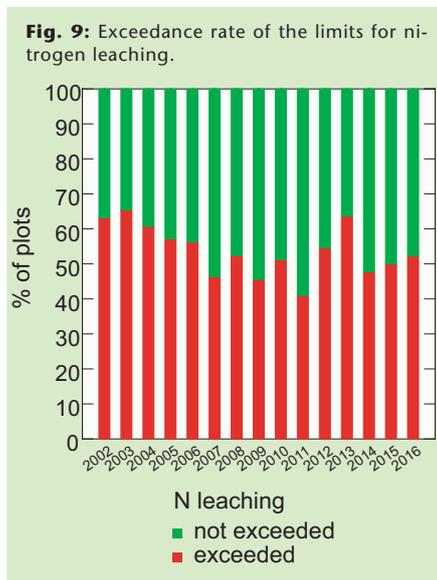


Fig. 9: Exceedance rate of the limits for nitrogen leaching.

To monitor soil acidification, soil solution is collected with suction cups called lysimeters. Our measurements show that soil acidification is progressing (Fig. 13), although we see a slowdown in a couple of plots probably caused by a decrease in nitrogen deposition.

Consequences of nitrogen deposition and soil acidification in forests such as vegetation changes or changes in soil microbiota, reductions of rooting or nutrient imbalances in trees are developing gradually and are not easily detectable. Visible symptoms like discolorations by Mg deficiency

have, however, increased in European beech. With our data we were also able to show that the risk for uprooting is increased strongly on acidified soils (19). Detecting the change and disentangling the effects is only possible with monitoring and evaluations.



Photo 8: Blackberry scrub (Frienisberg BE).

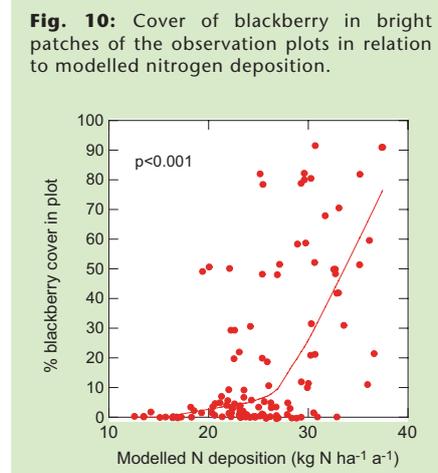
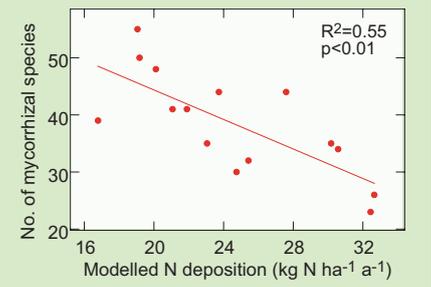


Photo 9: Several ectomycorrhizal species, i.e. *Cenococcum geophilum* and *Laccaria amethystina* on a European beech root from Zugerberg-Vordergeissboden (ZG).



Fig. 11: Number of ectomycorrhizal fungal species on European beech roots in 15 plots along a nitrogen deposition gradient (18).



The actual state of soil acidification can be estimated based on ground vegetation and geological maps (Chap. 7.5). This enables a risk assessment for forested areas. Such base saturation maps for the upper soil layer were developed for the cantons AG, BL, BS, FR, SO, TG and ZH at a scale of 1:5'000.

Nutrient sustainability of whole tree harvesting

Whole tree harvesting for wood energy increases biomass gain by one third, while the heating value of crowns is lower and, moreover, nutrient removal is multiplied in comparison to the use of stem wood only. This is especially the case for phosphorus. Base cation and phosphorus supply in forest soils occurs through mineral weathering or by atmospheric deposition (dust from agricultural land, volcanic dust, Sahara dust etc.). These sources are not sufficient to cover phosphorus removal by whole tree harvesting. For potassium and calcium, atmospheric dust covers removal in half of the studied forests (Ch. 9). If nutrient leaching driven by nitrogen deposition is considered, balances for calcium and magnesium are mostly negative. This shows that the nitrogen deposition found in

large parts of the Swiss plateau renders sustainable forestry difficult and whole tree harvesting is not sustainable as long as there is no nutrient return (Chap. 9).

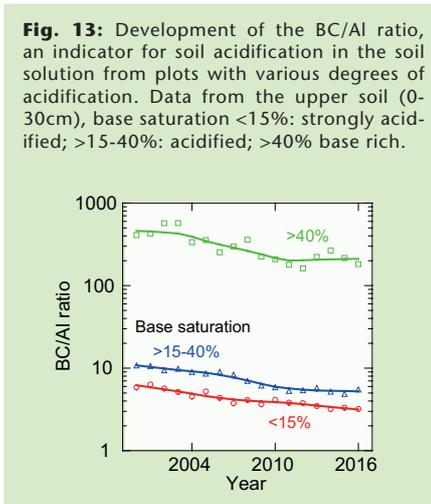
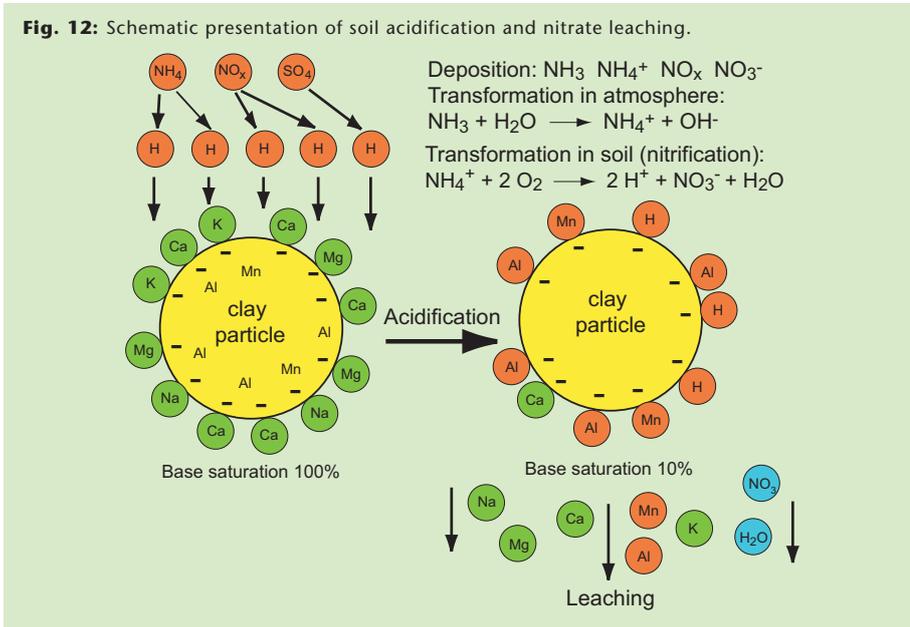
Ozone

Ozone is a strong oxidising agent and its effects on plants are well known (20). It causes characteristic visible injury on the foliage (21, Chap. 11.2). Ozone related growth reductions are, however, more relevant for forestry.

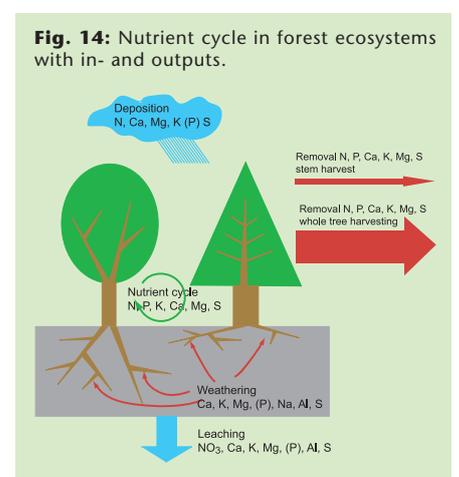


Photo 10: Processing of tree crowns to wood chips (Möhlin AG).

Since the 1980s, air quality control measures have reduced the precursors of ozone, i.e. nitrogen oxide and volatile organic compounds from traffic and industry. This has slightly reduced peak concentrations of ozone. However, the average ozone concentration (median) has remained stable or has slightly increased, while the base levels have augmented (24). Relevant for trees is not the atmospheric ozone concentration but the ozone flux through the stomata. Since 2000, ozone flux has decreased at four of six IAP-monitoring sites for Norway spruce, and for European beech at one of five stations.



Based on data from various fumigation experiments, a working group under the CLRTAP has specified Critical Levels for various plant groups expressed as phytotoxic ozone dose per projected leaf area and year (22). For European beech and Norway spruce, these critical levels are 5.2 and 9.2 $\text{mmol m}^{-2} \text{a}^{-1}$, respectively. These values are surpassed at all IAP ozone-monitoring sites across all years. Ozone effects can be observed in stem increment of adult trees. Based on ozone flux mapping, a total growth reduction of 11% in Swiss forests has been estimated (23).



Crown transparency of European beech is increased under high ozone levels (Chap. 2.1). Ozone affects also tree nutrition by reducing foliar nitrogen and phosphorus concentration both in European beech and Norway spruce (Chap.3.4). In general, ozone inhibits carbon transportation via phloem to the roots and thereby negatively affects growth of roots and mycorrhizal symbionts (18; Chap. 10.4).

Photo 11: Bronze discoloration in European beech induced by ozone (MuttENZ BL)

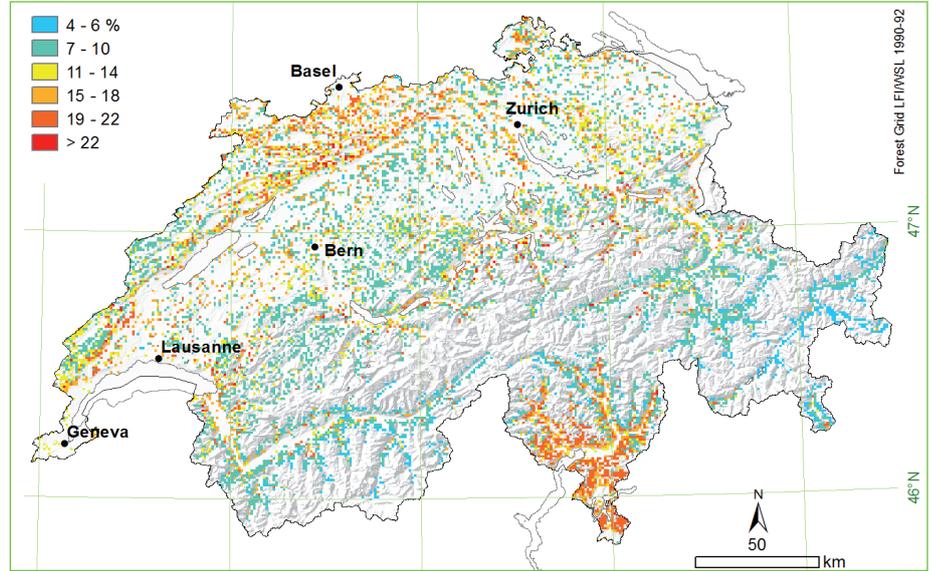
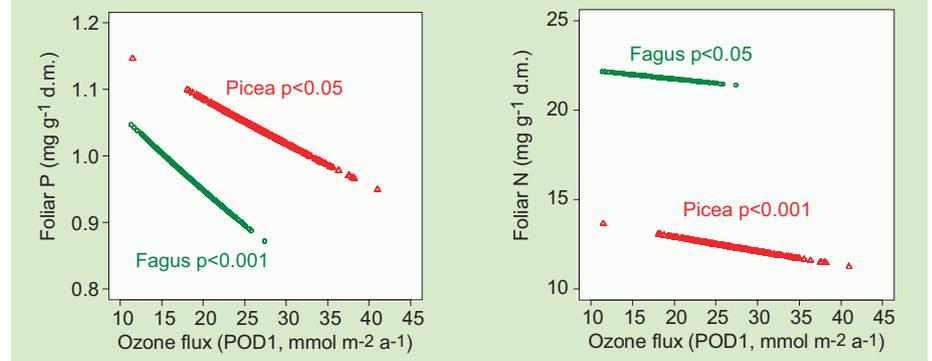


Fig. 15: Estimated growth reductions for trees caused by ozone (23).

Fig. 16: Relationship between the ozone level in the year preceding the leaf harvest and foliar nitrogen (left) and phosphorus concentration (right) in European beech and Norway spruce.



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