Introduction

Nitrogen Fluxes on an Intensive Investigation Plot in the North Tyrolean Limestone Alps

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Abstract. In the framework of this study, nitrogen fluxes on a limestone site are investigated. The major goals are the assessment of the nitrogen status, the estimation of the nitrogen budget and the evaluation of the nitrogen saturation. The investigation area, the intensive investigation plot and the research equipment are described.

Keywords: Limestone alps; nitrogen fluxes

Introduction

Early in the eighties, an attempt was made to prove effect-cause relationships between forest damage and the impact of air pollutants. Special emphasis was placed on the input of acid components. Among numerous forest dieback hypotheses, the so-called 'nitrogen hypothesis' was formulated (Nihlgard 1985) which attributes the 'new-type forest decline' to excess nitrogen input.

During the last 20 years, air pollution has considerably changed in Europe. While sulphur concentrations could be reduced considerably, emissions of nitrogen compounds could be reduced only slightly (Berge et al. 1995, EMEP 2000, Ritter et al. 1999). Research activities in the early and mid nineties revealed that nitrogen input from the open field through wet and dry deposition was generally under 30 kg ha^{-1} a^{-1} in the European countries (Smidt & Englisch 1998, **Fig. 1**).

Model calculations by the Bundesforschungsanstalt für Forst- und Holzwirtschaft (1997) showed an input of more than 21 kg ha^{-1} a^{-1} for Europe, on the average for the period between 1985 and 1995; the highest pollution being recorded in the Benelux countries, parts of Germany, Czech Republic and Poland. According to the investigation area, further surveys showed nitrogen depositions between 5 and 80 kg ha^{-1} a^{-1} (Ortloff & Schläpfer 1996).

The effects of airborne nitrogen input on forest ecosystems are rather complex. Continuous deposition may result in nitrogen saturation or oversaturation. Except for the direct impact of gaseous nitrogen compounds, the following consequences are important (Bobbink et al. 1992):

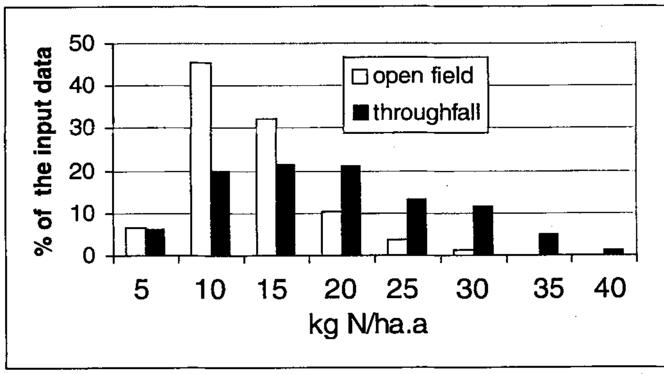

Fig. 1: Annual nitrogen input in forested areas in 5 kg N ha^{-1} a^{-1}-classes (upper limit; Austria, Germany, Switzerland, France, Italy, 1991–2000), percentage of the input data
White bars: open field (n = 929 input data); black bars: throughfall (595 input data)

- **Soil acidity:** High rates of nitrification add acidity to the soil. Possible consequences are a leaching of base cations and elevated concentrations of aluminium in the soil solution. Base cation losses can be partly offset by increased rates of chemical weathering.
- **Nitrogen eutrophication** leads to ecosystems that cannot retain nitrogen efficiently. Consequences are ground-water pollution and an increasing demand for other nutrients.
- **Increased productivity of forests.**

Numerous studies have proved that excess nitrogen input has a possible impact on forest ecosystems (overviews are provided in Glatzel 1990, Kölling 1991, Bobbink et al. 1992 and Ortloff & Schläpfer 1996). Other important contributions to this issue were submitted by Wright & Tietema (1995), Emmett et al. (1998), Hoek et al. (1998) and Schulze (2000). In addition to observations concerning the increase in growth (Nilsson & Wiklund 1992, 1995, Skeffington & Wilson 1988, Kenk & Fischer 1988), the relative reduction of root growth in comparison with the parts of plants above ground (Wilson & Skeffington 1994a,b), nutrient imbalances

(Schulze et al. 1989, Boxman et al. 1991) and deficiencies (Glatzel et al. 1987) were documented. There is also evidence for acidification of the soil (reduction of base saturation), Al-induced problems in the soil (Ulrich 1982) and increased leaching of basic cations (Rudebeck & Person 1998), changes in the quantity and quality of humus (changes in the C/N-ratio, Dise et al. 1998), changes in the composition of soil meso and microfauna and gaseous nitrogen losses (e.g. through an excess of nitrous oxides in the soil, Kölling 1991, Rigler & Zechmeister 1998). The physiological reaction of trees such as increased vulnerability to frost, insect pests and drought (Wellburn 1988, Aronsson 1980, Nilsen 1990) were described. Several authors reported on changes in the species spectrum of the soil vegetation (Kölling 1991), negative influences on mycorrhiza (Rühling & Tyler 1991, Hobbie et al. 1999) and ground-water pollution (water eutrophication and acidification; Kölling & Neustifter 1997). In contrast to the mentioned authors Binkley & Högberg (1997), do not attach much importance to negative effects of nitrogen input.

Many national projects, which address the effects of nitrogen input on the ecosystem, are integrated in European research programmes: The **NITREX-Project** (Nitrogen Saturation Experiments) investigated the nitrogen dynamics with artificially increased / reduced nitrogen rates (Wright & Tietema 1995, Tietema et al. 1998). The **EXMAN-Project** (Experimental Manipulation of Forest Ecosystems in Europe) dealt with the experimental manipulation of forest ecosystems in Europe (Kreutzer et al. 1998). Another project addressing a similar issue is conducted by Aber et al. (1998) in the Northeast of the United States.

At the national level, the following projects are carried out: The **Solling-Project** (Niedersachsen, Germany, Ulrich 1993, Bredemeier et al. 1999), studying complex interactions between fauna, vegetation, water and soil, the **MEXFO-Project** (Nordrhein-Westfalen, Ministerium für Umwelt, Raumordnung und Landwirtschaft 1993), focussing on air pollution research, the **ARINUS-Project** (Schwarzwald, Baden-Wuerttemberg, Feger 1992, Feger & Raspe 2000, Papen et al. 1994), investigating the impacts of rehabilitation measures and air pollution on the nitrogen and sulphur balance of the ecosphere and hydrosphere of forest sites, and the studies of the Bayreuth Institute for Terrestrial Ecosystem Research (**BITÖK** 1998, 2001) which has made the nitrogen problem a priority topic, by example of forest sites in the Fichtelgebirge (Bavaria).

The concept of Critical Loads (UN-ECE 1988, WHO 1995) forms the basis for the large-scale spatial risk assessment of nitrogen input. At the ecosystem level, the term **nitrogen saturation** is used as an important assessment criterion. Nilsson (1986) defined ecosystems from the production point of view to be saturated with nitrogen when there is no increase of the primary production through an increase of the nitrogen supply. According to Agren & Bassata (1988), nitrogen saturation is reached when nitrogen outputs from the ecosystem exceed the nitrogen inputs over a longer period of time. This approach follows the definition by Aber et al. (1989), which builds on the concept of Critical Loads (UN-ECE 1988) used also for the studies under the NITREX and EXMAN programmes (the related papers in this Special Issue also refer to this definition): **Nitrogen saturation of an ecosystem is considered to be reached when the nitrogen offer exceeds the needs of plants and microbes.** The moment when saturation is reached depends on the deposited nitrogen quantities, the vegetation type, the soil type and the forest management. High N-concentrations over longer periods may result in N-saturation of the forest soil (Fenn et al. 1996, Butterbach-Bahl et al. 1997, Goulding et al. 1998). In this case, the nitrogen input through atmospheric deposition will be absorbed no more and thus lost from the system either through leaching of nitrate or through emanation of N_2O, NO and N_2.

According to various authors, input exceeding 15 kg may cause nitrate losses, while an input of more than 25 kg ha^{-1} a^{-1} generally causes nitrate losses (Dise & Wright 1995). When increasing the input to more than 55 kg N ha^{-1} a^{-1}, the output was up to 30 kg N ha^{-1} a^{-1} (**Fig. 2**).

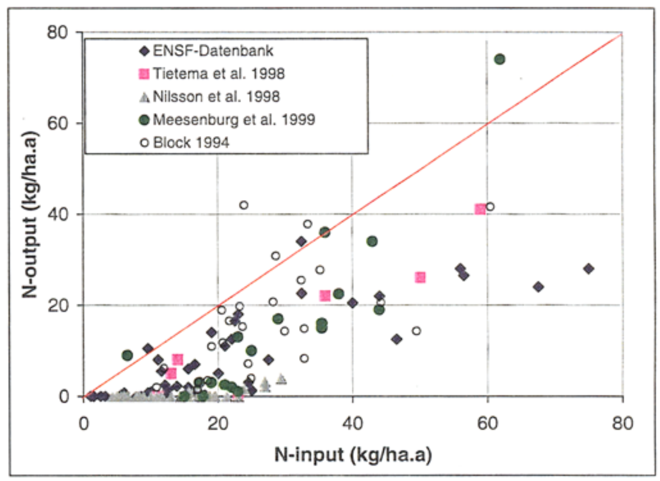

Fig. 2: N-input and N-output of forest ecosystems
ENSF-Data base assessment of N and S-fluxes, Hauhs 1989, Hauhs et al. 1989); Tietema et al. 1998 (NITREX-Project); Nilsson et al. (1998); Meesenburg et al. (1999, Solling-Project); Block (1994, Rheinland-Pfalz)

The nitrogen cycle in (forest) ecosystems is characterised by a multitude of fluxes between the individual pools, as well as by internal and external fluxes (Schenk 1998, Herman et al. 2001). The nitrogen demand of a forest ecosystem consists of nitrogen uptake of the microbial, fungal and the plant biomass. Between the roots and the soil microbes, especially in soils with wide C/N-ratios (Aber 1992, Aber et al. 1993), there is a strong competition for the limited stock of mineralised nitrogen which may impede the nitrogen uptake in the tree biomass. The (man-made) deposition of plant available nitrogen in the form of NH_3 and NO_3 may result in an increased incorporation into the plant biomass which may also take place over direct uptake from foliage, thus exceeding the need of the system adapted to N-deficiency, and may cause the output from the ecosystem (in the form of easily soluble NO_3). According to studies by Tietema et al. (1998), only relatively small portions (10 to 30% as a maximum) of the additional nitrogen are incorporated from the deposition into the plant biomass. According to Aber et al. (1998), major portions will be retained in the soil, even in the case of long-lasting continued input. Three classes of soil processes, that is immobilisation through microbes via biomass production or abiotic incorporation into the organic soil substance, as well as the transformation into organic nitrogen by mycorrhiza without biomass production, are discussed. According to studies by Gundersen et al. (1998), a major part of the incorporated nitrogen is stored in the soil of originally nitrogen-limited spruce ecosystems, but a part is directly exported from the system hydrologically in the form of nitrate. At the moment, the atmospheric nitrogen deposition changes the transformation processes of nitrogen in the soil. An increase in net-mineralisation has been observed.

1 Site and Scope of Investigation

The focal point of the interdisciplinary investigations (**Fig.** 3) is located in the North Tyrolean Limestone Alps (growth areas 4.1 and 2.1, Kilian et al. 1994), which occupy a surface of 380,000 ha; 68% are covered with forests. The share of protection forest is 42% and considerably above the Austrian average.

In addition to air pollution, traditional land management methods such as forest pasture, litter raking, pruning and high game density are the most important man-made risks in the North Tyrolean Limestone Alps. The region is also subject to the direct and indirect demands of mass tourism (Herman & Smidt 1996).

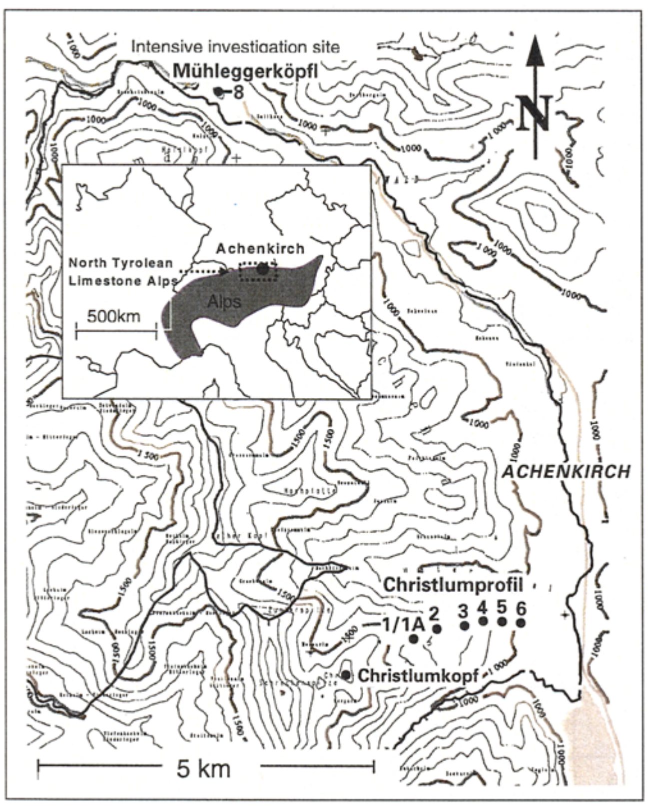

Fig. 3: The North Tyrolean Limestone Alps, investigation area Achenkirch, with intensive investigation site 'Mühleggerköpfl' (8) and with further investigation plots (Schulterberg, 7, 9, 10; Christlumprofil, 1–6)

Between 1983 and 1995, depending on the year, the nitrogen supply of needles of *Picea abies* of the Austrian Bio-Indicator Grid was either 'not sufficient' or 'deficient' on 40–60% of the sample plots (Stefan & Fürst 1998). The annual Tyrolean crown condition surveys revealed an increased degree of defoliation in the North Tyrolean Limestone Alps since 1984; in 1997 almost 50% of the sample trees showed significant defoliation. In 1998, an aerial photographic assessment of crown condition of an area of 115 km², including the investigation site at Mühleggerköpfl, was done in a regular grid (250 x 250 m, 5091 tree crowns). According to UN-ECE-classification (UN-ECE 1994), 33% of the trees are classified as 'not defoliated' and 67% as 'defoliated' (of which 27% are 'damaged' and 1.5% dead; Gärtner et al. 2000, Gärtner 2001). The region of Achenkirch, as well as of the North Tyrolean Limestone Alps, have to be classified as 'damaged' (Amt der Tiroler Landesregierung 1998).

1.1 The Investigation area of Achenkirch

The investigation area of Achenkirch shows some typical characteristics of an ecosystem in the North Tyrolean Limestone Alps: 61% of the forest is classified as protection forest, 39% as production forest. An ecological characterisation is provided by Englisch & Starlinger (1995, 1996). The main tree species are *Picea abies* (52%) and *Fagus sylvatica* (19%). *Pinus cembra* is represented with 14%; further tree species are *Larix decidua* (4%), *Abies alba* (4%), *Pinus sylvestris* (2%) and other species (Gärtner et al. 2000).

- **Soils:** The median of the nitrogen contents of the soils in the investigation area of Achenkirch (Christlum profile, Schulterberg profile, Mühleggerköpfl) was 10.0 mg g^{-1} (0–5 cm), 6.6 mg g^{-1} (5–10 cm) and 1.9 mg g^{-1} (20–30 cm). It was clearly above the Austrian average of carbonate-influenced soils (Forstliche Bundesversuchsanstalt 1992).
- **NO_2-concentrations and input:** Since 1991, the NO_2-concentrations were far beyond the effect-related limiting values (Smidt et al. 2000), whereas a downward trend was noted as regards the annual average. The nitrogen input from the open field was 12 kg ha^{-1} a^{-1} on the average (Berger 1995, Smidt 2000). From November 1995 to October 1996, the total nitrogen deposition (total from wet, dry and occult deposition) at the Christlum profile at three sea levels was 20–28 kg ha^{-1} a^{-1} (Kalina 1997). The modelling of Critical Loads for nitrogen showed critical loads of 15–25 kg ha^{-1} a^{-1} for the investigation area (Knoflacher & Loibl 1996). Detailed information is provided by Smidt et al. (1995, 1996); Herman & Smidt (1995, 1996) and Herman et al. (1998).

1.2 The intensive investigation plot at the Mühleggerköpfl

The Mühleggerköpfl (920 m a.s.l.) is located west of the former customs station Achenpass. It is a completely isolated hill reaching 120 m above the valley bottom, formed from dolomite ('Hauptdolomit', Ampferer 1950). The western slope has a high inclination towards the creek Achenbach. The small mountain ridge presents a variety of silvicultural management types. A special feature of the Mühleggerköpfl is the exposed location of the stands around the summit plateau and structures which change very quickly within a small scale (tree age, canopy density). With respect to ecological factors, the Mühleggerköpfl can be considered as typical for the growth area 4.1.

The intensive investigation plot was characterised by Englisch & Starlinger (1995, 1996) as warm, central montane spruce-fir-beech-forest. The potential natural forest community makes the transition from central montane Aposerido-Fagetum caricetosum albae to deep montane Carici albae-Fagetum. Indicators of flora and soil suggest a thermophile variety of Aposerido-Fagetum saniculetosum. The plant species of the site unit are indicators of light and higher temperature. Plant species typical for pasture can be found. The soil types of the intensive investigation plot are Chromic Cambisols of intermediate depth (30–60 cm) as well as Rendzic Leptosols, which are mostly shallow (15–30 cm) or of intermediate depth (30–60 cm). The measuring profiles (soil solution) are in Chromic Cambisol and Rendzic Leptosol. The soil types have a high small-scale variability of the skeleton content. Englisch (2001) provides a detailed description of the site. N-stocks are high, while close C/N-ratios (16–18) suggest favourable transformation conditions for N-mineralisation and nitrification. The carbonate content of the soil is extremely high and marked by the presence of dolomite (Mutsch 2001).

The 125-year-old stand is dominated by spruce. Pine and beech occur isolated or in groups. According to the nine-grade scale for the assessment of hemeroby (Grabherr et al. 1997), the naturalness is classified with 4.5 (moderately to strongly altered).

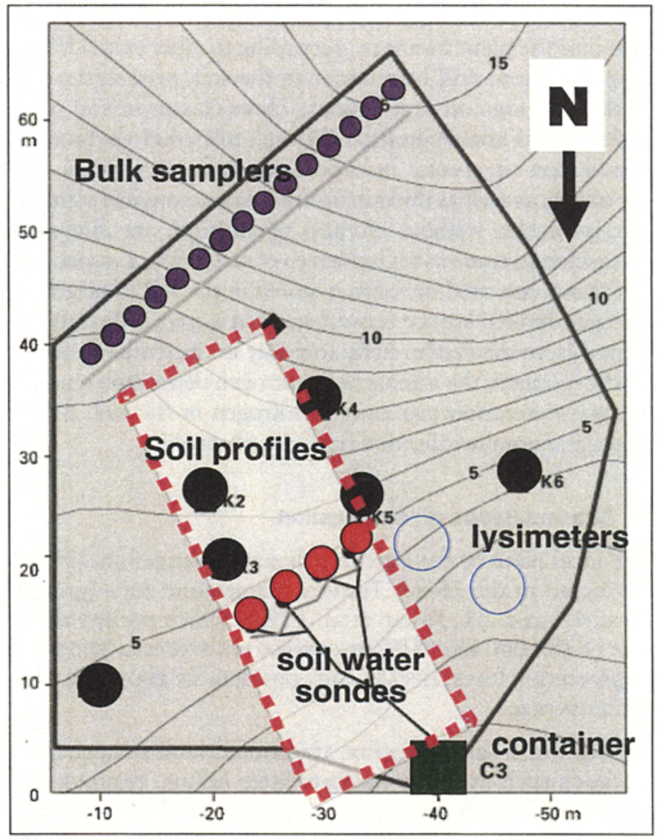

Fig. 4: The intensive investigation plot and measurement facilities at Mühleggerköpfl. Contour line: relative altitude [m] above the container site (900 m a.s.l.)

Picea abies shows a dominant height of 27.1 m, a basal area of 40 m^2 ha^{-1}, a growing stock of 548 m^3 ha^{-1}, which corresponds to yield class 6 (yield table for spruce, Bavaria). For the summit area, the dominant height is 19.1 m, the basal area is 20 m^2 ha^{-1}, the growing stock is 156 m^3 ha^{-1}, which corresponds to yield class 2.5 (Österreichischer Agrarverlag 1975).

The location and the measurement facilities at the intensive investigation plot Mühleggerköpfl are shown in **Fig. 4. Table 1** provides basic data of the intensive investigation site.

Table 1: Basic data on the intensive investigation plot; mean temperature values and precipitation sums at the intensive investigation plot and reference values of the comparison station of the Central Institute for Meteorology and Geodynamics, and of TIWAG ('Achenkirch Pumpwerk') located at 10 km SSE of the intensive investigation plot (Gattermayr 2001)

Coordinates	11° 38' 21" East; 47° 34' 50" North
Tree species composition	approx. 90% spruce, 10% beech
Location	Karwendel
Intensive investigating plot	ca. 1/3 ha
Sea level at the monitoring plot	895 m
Soil	Rendzic Leptosol / Chromic Cambisol

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**Average 1991–1998**	**Average 1981–1990**	**Average 1991–1995**
Temperature (°C): 'Catchment' Mühleggerköpfl (Container C2)					6.2	6.9	–	–	–
Temperature (°C): Reference values Achenkirch Pumpwerk	5.3	4.9	6.0	6.1	5.8		6.4	–	–
Precipitation (mm; Totalisator)				1691	1977	1931	–	–	–
Precipitation (mm): Reference values Achenkirch Pumpwerk	1585	1457	1469	1478	1688		–	1395	1451

Table 2: Measurement facilities and parameters (ions: Cl^-, NO_3^-, SO_4^{--}, NH_4^+, Na^+, K^+, Ca^{++}, Mg^{++}); stable isotope relationships ($^{15}N/^{14}N$-ratio, $^{18}O/^{16}O$-ratio); meteorological parameters (temperature, air humidity, radiation, wind direction, wind velocity, air pressure)

Measurement facilities		Parameters
Container C 1	Fog sampler (occult deposition)	pH, conductivity, ions; nitrate-isotope relationships
	Passive samplers (dry deposition)	SO_2, NO_2, NH_3
	Stack filters (dry deposition)	HNO_3, SO_4^-, NO_3^-, NH_4^+-aerosol, Na^+, K^+, Ca^{++}, Mg^{++}
	WADOS (wet deposition)	Quantity, pH, conductivity, ions; nitrate-isotope relationships
Container C 2		SO_2, NO, NO_2, O_3; meteorological parameters
3 bulk-open field collectors (wet depositions)		Quantity, pH, conductivity, ions Nitrate-isotope relationships
15 crown throughfall bulk-collector (wet deposition)		Quantity, pH, conductivity, ions; $^{15}NO_3$-N
1 hydrometeorological station		Meteorological parameter incl. evaporation degree, tub water level and water temperature close to the surface, snow depth
32 gypsum blocs (soil solution)		Matrix potential
6 Theta sondes (soil solution)		Water percentage
10 Vitel sondes (soil solution)		Water percentage, soil temperature
16 suction cups (soil solution)		Quantity, pH, conductivity, ions; nitrate-isotope relationships
3 surface runoff gullies with 2 collection vessels		Quantity, pH, conductivity, ions; nitrate-isotope relationships
6 gas-measuring chambers		N_2O^-, CO_2 , CH_4
18 ion exchanger		NO_3^-- and NH_4^+-leaching, N-gross mineralisation
24 soil samples		NO_3^- and NH_4^+- concentration, N-net mineralisation, N in microbial biomass, extractable glucose equivalents, gravimetric water content
18 observation plots		Litterfall and decomposition velocity
Forest lysimeter		Nitrate-isotope relationships; 2 ^{15}N-applications: Incorporation of $^{15}NO_3$-N into microbial biomass, in roots and sprouts of ground vegetation and soil fauna; $^{15}NO_3^-$-output from a soil depth of 0–10 cm and denitrification as $^{15}N_2O$
Snow lysimeter		Nitrate-isotope relationships
Container C 3		
Soil samples (4 profiles)		Dry mass, pH (H_2O), pH ($CaCl_2$), CO_3^-, $C_{org.}$, $N_{ges.}$, C/N, humus content; P, K, Ca, Mg, Fe in the acid extract; K, Ca, Mg in the $BaCl_2$-extract; Cl^-, NO_2^-, NO_3^-, SO_4^- in the water extract; nitrate-isotope relationships

2.3 Scope of Investigation

Measuring facilities and parameters. Several working teams are concerned with the measurement of element budget, growth and population dynamics, from the soil-rooting zone up to the crown. These figures are entered into a data base (Schaffer 2001). The measuring facilities and parameters which were the basis for the calculation and modelling of the element budgets are indicated in **Table 2**.

2 Objectives

The aim of the forest damage surveys in the area of Achenkirch which have been conducted since 1990 is to assess the risk for the mountain ecosystems on a broad interdisciplinary basis. Litter raking and pruning activities during decades are responsible for the poor nutrition supply of the local forests (Englisch 2001). As a consequence, these forests are now in a very bad condition (crown condition, growth, Gärtner 2001), below others suffering from lack of nutrition (Stefan & Fürst 1998), of which nitrogen deficiency is the most frequent.

Air pollution and its impact on forest trees play an essential role in the research into the cause-effect relationships (Herman et al. 1998). Open field measurements (Kalina et al. 1998, Smidt 1998) and modelling during recent years have identified that nitrogen input exceeds Critical Loads in mountain forest ecosystems of the North Tyrolean Limestone Alps (Herman et al. 2001). Therefore, the question arises in how far the measured nitrogen input affects sites which show nitrogen deficiency at the moment.

In order to obtain more information concerning pools and fluxes, and to extend the knowledge of the risk due to nitrogen on a limestone site, the following objectives were worked out within an interdisciplinary project:

- Nitrogen status of the investigated area,
- Nitrogen budget using internal fluxes,
- Nitrogen saturation,
- Impact of the nitrogen status on the ground water quality.

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