Research Articles

Simulation of Soil Hydrology and Establishment of a Nitrogen Budget of a Mountain Forest

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Abstract. The water fluxes through the mountainous forest ecosystem 'Mühleggerköpfl' were simulated by means of the mechanistic soil physical model Hydrus 1D. The objective was to set up a nitrogen budget in order to decide if the ecosystem accumulates nitrogen or if nitrogen leaks from the site. The simulated annual loss of N by percolation ranges between 0.4 and 1 g N m^{-2} yr^{-1} and is smaller than the annual input by bulk and occult deposition, which combines to approx 1.2–1.5 g N m^{-2} yr^{-1}. Obviously the forest soil presently accumulates N. With an N input-rate exceeding the N output, the operationally defined status of N saturation is not yet reached. Comparing the magnitude of the N pool in the soil (several kg N m^{-2}) with the rate of the annual increase (a few g N m^{-2} yr^{-1}), the process of N saturation is apparently slow.

Keywords: Alps; forest soil hydrology; N budget; N saturation; nitrogen; spruce forest

Introduction

Among all biogeochemical nutrient fluxes, that of nitrogen has been changed by such human activities as combustion of fossil fuel, fertilizer application, livestock, and the burning of biomass to the greatest extent. Ecosystems are expected to become N saturated (Vitousek et al. 1997). There are, however, ecosystems with a strongly diminished N pool. Many forests in Austria have a long history of nutrient exploitation and nitrogen is commonly the growth-limiting element. The continuous addition of excess nitrogen is expected to have a noticeable effect on biogeochemical fluxes and may in the long run lead to N eutrophication with negative effects on forests (Aber et al. 1995, 1998). Currently, the productivity of forests in Central Europe is increasing (Spiecker et al. 1996). Evidence for N eutrophication was found in forests with high rates of N deposition, but it was proposed that even low rates of N deposition can affect sensitive forest ecosystems (Baron et al. 1994, 2000, Emmett et al. 1998). We wanted to substantiate if the concern of N eutrophication is valid at our study site and if forests on shallow dolomite-derived soils are particularly sensitive towards high rates of N deposition. It is unclear yet, whether forests respond to increased nitrogen inputs with higher productivity due to the increased N availability, or the N retention proceeds to an N level where the system changes dramatically. Ecological theory suggests that gradual changes in one factor are buffered for a certain time, dependent on the system's resilience, but abrupt changes are inevitable (Scheffer et al. 2001).

The Alps form an abrupt barrier and efficiently intercept rainfall. Although nitrogen concentrations in the rain are low, the mere quantity assures that the deposition load is high. Moreover, fog can contribute a large part of the nitrogen deposition (Binkley et al. 2000, Fenn et al. 2000, Igawa et al. 1998). At calcareous sites in the mountain area, there are natural obstacles to overcome when establishing a nutrient budget. Field measurement of the nutrient output by leaching is impossible because no defined pathways of the soil water exist. In the coarse-textured soil, the water flux varies on the smallest spatial scale and streams carry water only temporarily (Hagedorn et al. 1999). The incoming water is mostly absorbed in the porous soils and gravitates along variable paths.

We applied the mechanistic soil physical model Hydrus (Simunek et al. 1998) to simulate soil hydrology. It requires detailed soil physical and meteorological input data. The steps were to (i) parameterize the models with the existing data set, (ii) run the simulation, (iii) identify/corroborate the major factors, (iv) do an error analysis upon unrealistic values of modeling results, (v) refine the parameters, and (vi) obtain answers from the simulation.

1 Methods

1.1 Site and stand

The study site Mühleggerköpfl, province of Tyrol (11°38'21"E 47°34'50"N) is located on a N-NE facing slope in 895 m a.s.l. The bedrock is dolomitic limestone from which a mosaic of rendzinas and terrae fuscae has developed (Englisch 2001). The total N deposition is 1.2-1.5 g N m^{-2} yr^{-1}. The more than 120-year-old stand consists mainly of Norway spruce.

1.2 Water balance

The water balance consists of the incoming precipitation, the evaporation from the canopy and the surface, the transpiration, and the vertical and lateral output of the system.

The 'precipitation above the canopy' was measured bi-weekly at a small, clear cut adjacent to the stand. Measured precipitation data were harmonized with the daily measurements of a meteorological station and were converted to daily data.

The throughfall was collected bi-weekly. A linear regression function with zero intercept between measured amounts of precipitation above and below the canopy was calculated. The regression was used to derive values for the daily precipitation below the canopy. Curvilinear models did not improve the data quality and could be ignored.

Evapotranspiration was calculated with the simulation program Brook-90 that uses the Penman-Monteith formula (Federer 1995). Climate data (precipitation above the canopy [mm], minimal, maximal, mean air temperature T_m [°C], solar radiation [W m^{-2}], relative humidity rH [%]) were taken from the local climate station at the experimental site. The vapor pressure deficit D_p [hPA] was calculated from the saturated vapor pressure E_s [hPa] and actual vapor pressure e [hPa], respectively, and the mean air temperature, and relative humidity (Eq. 1).

$$D_p = E_s - e \quad (1)$$

$$E_s = 6.1054 * EXP(17.27 * T_m/[237+T_m])$$

$$e = E_s * rH / 100$$

The climatological input data set for HYDRUS requires the distinction of root and soil respiration. The calculated evapotranspiration was assigned to root respiration, if the minimum air temperature was above freezing point, because Norway spruce starts to transport water as soon as positive temperatures are reached (Körner 1999). If the minimal temperature was below 0°C, it was assumed that only evaporation from the soil, but no transpiration, took place.

1.3 Soil moisture / soil solution chemistry

At four soil profiles, the water content was recorded at 3 soil depths every 30 min by means of thermocouples. Samples of the soil solution were collected every two weeks by means of suction cups and were analyzed. The technical equipment of the site is described in Feichtinger & Scheidl (2001), the chemical analysis in Smidt (2001).

1.4 The soil profile

In the field, we encountered a considerable small-scale variability of the soil profile morphology. A reference profile was chosen as representative soil for the site (Englisch 2001). The root distribution was assessed by visual inspection of the reference profile. This parameter partitions the water uptake, which equals the calculated transpiration, over the profile. It reflects the shallow rooting system of Norway spruce: the layer 0–6 cm contains 60% of the roots; 30% of the roots are found at 6–25 cm and the remaining 10% between 25 and 40 cm. A water retention function was obtained by calibrating a water-flow model against measured data (**Table 2**).

The soil physical characteristics, derived from retention curves that had been generated from undisturbed soil samples in the lab, did not satisfyingly reflect the site (Feichtinger & Scheidl 2001).

1.5 Simulation model

For modeling the water and solute transport, we used the model HYDRUS 1D Version 2.01 (Simunek et al. 1998). HYDRUS-1D uses the Richards' equation for simulating variably-saturated flow and Fickian-based convection-dispersion equations for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots. The solute transport equations consider convective-dispersive transport in the liquid phase, as well as diffusion in the gaseous phase. The transport equations also include provisions for nonlinear non-equilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero-order production, and two first-order degradation reactions: one which is independent of other solutes, and one which provides coupling between solutes involved in the sequential, first-order decay reactions. The model includes modules for the discretization of the soil profile into finite elements, and definition of the vertical distribution of hydraulic and other parameters characterizing the soil profile. It is a tool for predicting water and solute movement in the vadose zone, and extrapolating information from a limited number of field experiments to different soil and climatic conditions. HYDRUS-1D does not handle preferential water flow and may fail for extremely nonlinear flow and transport problems.

Table 1: Summary of key values of the water balance at the Mühleggerköpfl site

Year	Precipitation [mm]	Throughfall [mm]	Evapotranspiration [mm]	Infiltration [mm]	Outflux [mm]
1998	1691	1489	702	1300	787
1999	1976	1729	817	1510	873
2000 (I–XI)	1818	1577	792	1460	800

Table 2: Parameters of the van Genuchten (1980) model derived from field measurements for individual layers. Θ_r and Θ_s are residual and saturated water contents (1=100%), respectively, α and n are dimensionless shape parameters, K is the hydraulic conductivity of the saturated soil (cm day^{-1})

Layer	Depth	Θ_r	Θ_s	α	N	K_S
Forest floor	5–0 cm	1E-005	0.57	0.003	1.147	985.3
A	0–5 cm	0.08	0.293	0.0025	2.919	27.99
C1	5–25 cm	0.19	0.409	0.0023	1.547	23.13
C2	25–50 cm	0.013	0.179	0.0425	1.374	21.39
C3	>50 cm	0.001	0.239	0.016	1.106	22.203

For simulation purposes, the soil profile down to 75 cm depth is discretized into a series of 100 finite elements. We set the density of the elements to a high value in the upper part of the soil profile, where we expect larger pressure gradients, and gradually increased the element size downwards.

1.6 Calibration of model parameters, validation of simulated results, setting up a nitrogen budget

For the calibration of the model using the soil physical properties from Table 2, we took data of the first year of measured water contents. The parameters were optimized in order to provide the best possible fit between measured and simulated values for three depths and one year. The parameters were validated by comparison of simulated and observed water contents of the two remaining years and were refined until the extent and the temporal pattern of changes in the soil water content were reflected. In general, the measured data showed a larger amplitude than simulated water contents. The correlation between measured and simulated water contents varies between r=0.35 and r=0.40 and is significant (α <0.1%) (**Fig. 1**).

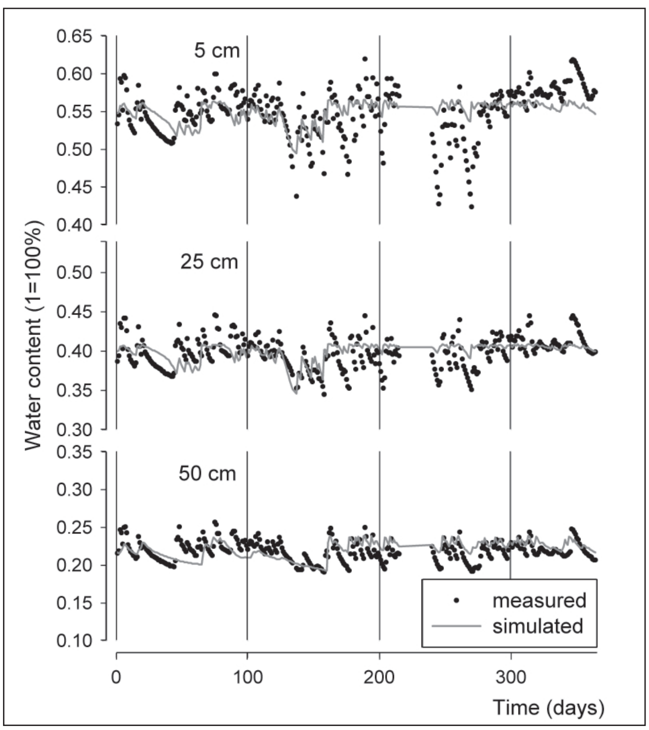

Fig. 1: Calibration of soil physical parameters with field measurements of the soil water content in the year 1998. Note different scales for individual soil depths at the y-axis

2 Results

The main water transport processes, *i.e.* cumulative infiltration, transpiration, and outflux (=seepage flux) are shown in **Fig. 2**. At any time, the amount of water reaching the soil surface is larger than the water demand of the forest. Obviously, there is an almost constant supply of water to the soil surface. The episodes of outflow are less frequent, because the soil temporarily retains water. The annual rainfall varies less than the rate of the throughfall that ultimately reaches the soil surface. The years

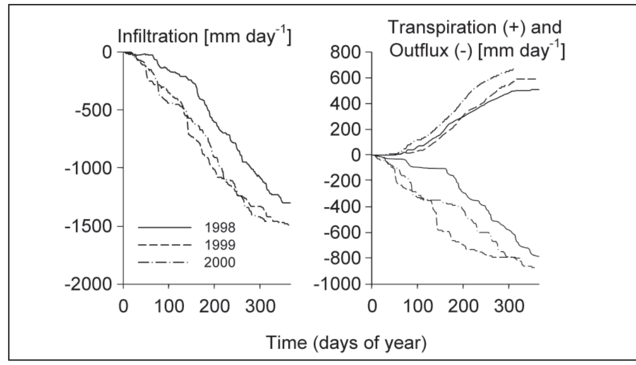

Fig. 2: Water fluxes into and out of the soil at the experimental site Mühleggerköpfl, displayed as cumulative functions for the individual years of the experiment

1999 and 2000 were considerably wetter than 1998. The rate of the outflux of water shows more variability than the water input, because the water flux density quickly responds to heavy rain. Single intense precipitation events (e.g. May 1999) had a strong influence on the total outflux from the system. A number of heavy rain periods in the second half of the year 2000 led to similarly high seepage rates.

The temporal trend of the water retained in the soil profile, the 'pressure head', shows only small differences between the upper and lower parts of the soil (data not shown). The pressure head is somewhat smaller at the top of the soil because roots tap the water resource. Despite some temporal fluctuation of pressure heads, the trees never experience a water deficit. The amount of rainfall is sufficiently large to supply the plants, even though the water-holding capacity of the soil is relatively low. Small infiltration events (i.e. rain reaching the soil surface) are retained in the soil profile, whereas intensive rain almost immediately leads to the formation of water outflux from the soil. Water saturation is reached at approx. 220 L m^{-3}. The simulated water content in the entire soil profile varies between 180 and 210 L m^{-3} most of the time.

For the estimation of the N output of the soil, we used the nitrate concentrations in 50 cm soil depth and the simulated outflux of the soil (**Fig. 3**; see also Fig. 2). The nitrate concentrations were considerably higher in 1998 than in the subsequent years.

Multiplying the nitrate concentration in the soil solution with the flux density of water yields an estimate of the annual N output. The calculated output of NO_3-N is 1.2 and 0.4 g m^{-2}

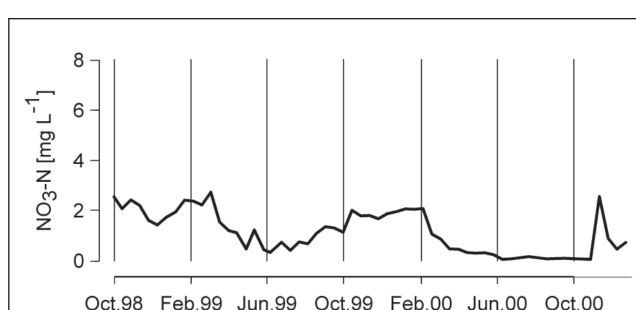

Fig. 3: Temporal trend of nitrate concentrations in the soil solution for years 1999 and 2000; depth 50 cm

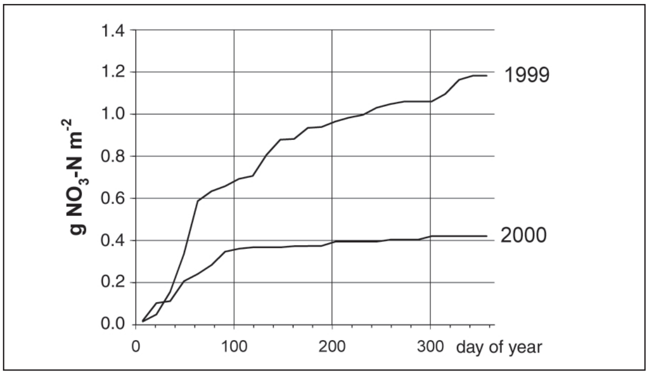

Fig. 4: Nitrate-N flux out of the soil at the experimental site Mühleggerköpfl, displayed as cumulative functions for the years 1999 and 2000

for the years 1999 and 2000, respectively (**Fig. 4**). The value for the year 2000 reflects January to October only. Nevertheless, only initially (1998) high rates of leaching have been observed, but the values are low in the years 1999 and 2000.

3 Discussion

Precipitation events at the experimental site Mühleggerköpfl are frequent and the entire soil profile stays moist all year round. The pore space of the soil profile down to 1 m allows it to retain about 220 L water. This is a high volume, considering the high content of coarse material. The high frequency of rain causes the quick displacement of soil water. Events of heavy rain quickly fill the soil pores with water and frequently lead to water flux out of the soil. The water demand of the vegetation can be fulfilled and water stress is rare or absent.

The small-scale spatial variability of the soil morphology at the Mühleggerköpfl makes predictions about the water flux and the N dynamics in the entire catchment uncertain. A detailed representation of the range of soil physical properties and soil profile morphologies is tedious. Instead, we chose one reference soil profile. The measured soil physical parameters were rather variable within all soil depths, although the combination of the encountered water retention characteristics and depths of soil horizons lead to surprisingly similar values for water contents and water fluxes in the entire soil profile. Apparently, small-scale differences are compensated within each soil profile.

The simulated N output varies between 0.4 and 1 g N m^{-2}. The Mühleggerköpfl is still in the state of N accumulation. Early stages of N saturation may not be spectacular, and nitrate leaching is usually a good indicator for N saturation. Earlier experiments have identified nitrate leaching as an indicator of forest system disturbance (Lamersdorf et al. 1998, Mellert et al. 1998). Mountain forests in the Alps have until now been N limited and the N retention capacity may prevail for some time in the future. The present rate of the annual N accumulation is negligible in relation to the total soil N pool.

The mechanism of N retention is not yet identified. Both biotic and abiotic mechanisms have been suggested (Dail et al. 2001, Kay et al., in press). The adsorption capacity for NH_4 is only moderate due to the low loam content of the coarse textured soil. The incorporation of N in the soil organic matter is likely the central process. Over time, the increase in its N content will become evident from a decreasing C:N ratio. This hypothesis can be verified only after several decades.

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