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Impacts of climate and management on water balance and nitrogen leaching from montane grassland soils of S-Germany☆

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ABSTRACT

In this study water balance components as well as nitrogen and dissolved organic carbon leaching were quantified by means of large weighable grassland lysimeters at three sites (860, 770 and 600 m a.s.l.) for both intensive and extensive management. Our results show that at E600, the site with highest air temperature (8.6 °C) and lowest precipitation (981.9 mm), evapotranspiration losses were 100.7 mm higher as at the site (E860) with lowest mean annual air temperature (6.5 °C) and highest precipitation (1359.3 mm). Seepage water formation was substantially lower at E600 (−440.9 mm) as compared to E860. Compared to climate, impacts of management on water balance components were negligible. However, intensive management significantly increased total nitrogen leaching rates across sites as compared to extensive management from 2.6 kg N ha^{-1} $year^{-1}$ (range: 0.5–6.0 kg N ha^{-1} $year^{-1}$) to 4.8 kg N ha^{-1} $year^{-1}$ (range: 0.9–12.9 kg N ha^{-1} $year^{-1}$). N leaching losses were dominated by nitrate (64.7%) and less by ammonium (14.6%) and DON (20.7%). The low rates of N leaching (0.8–6.9% of total applied N) suggest a highly efficient nitrogen uptake by plants as measured by plant total N content at harvest. Moreover, plant uptake was often exceeding slurry application rates, suggesting further supply of N due to soil organic matter decomposition. The low risk of nitrate losses via leaching and surface runoff of cut grassland on non-sandy soils with vigorous grass growth may call for a careful site and region specific re-evaluation of fixed limits of N fertilization rates as defined by e.g. the German Fertilizer Ordinance following requirements set by the European Water Framework and Nitrates Directive.

1. Introduction

Due to human activities, production of reactive nitrogen (N) has been globally increased during the last few decades (Galloway et al., 2003). Nitrogen in soils that is not used by plants and microbes can be subject to gaseous and leaching losses. Significant amounts of fertilizer N input to agricultural ecosystems, i.e. 34% and 18.4% in US and EU 27 countries, respectively, are still entering surface waters and aquifers leading to eutrophication and deterioration in drinking water quality (de Vries et al., 2011; Houlton et al., 2013). Agricultural N input is one of the main sources of water pollution in Western Europe calling for a better balance between agricultural production and environmental impacts (Oenema et al., 2003; Tilman et al., 2002). With the transposition of the European Water Framework Directive (EC, 2000) and the Nitrates Directive (EEC, 1991) this challenge has become a matter of urgency. The requirements of the Nitrates Directive are implemented in Germany mainly in the Fertilizer Ordinance (DüV, 2007) which currently restricts the application of organic fertilizers such as cattle slurry to 170 and on specific request to 230 kg N ha^{-1} yr^{-1} for cut grasslands aiming to reduce nitrate export from agricultural sources to water bodies and to ensure improved water quality.

Although these polices have contributed to reduce N losses to the hydrosphere, in the EU agricultural regions there are still about 80% of groundwater bodies exceeding nitrate concentrations of 25 mg NO_3 l^{-1}, and approx. 20% above the maximum admissible concentration of 50 mg NO_3 l^{-1} (Colombo et al., 2015; Velthof et al., 2009). Generally, N conservation in grasslands is improved as compared to arable land since growing seasons are longer and grassland plants use N more efficiently (Di and Cameron, 2002). Therefore, it has recently been debated that uniform thresholds as set by the Nitrate Directive might need to be carefully re-evaluated for grassland ecosystems (Schröder et al., 2010). Yet, there are more

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challenges to synchronize N availability with plant demand for organic N fertilization e.g. by slurry, which is the most typical way of nitrogen supply to grassland systems.

Montane grasslands, receiving high precipitation and having soils with high organic matter contents, have been shown to be vulnerable to nitrogen leaching in particular with excessive fertilization (McGovern et al., 2014). This highlights the need of optimizing agricultural management of montane grasslands (Loucougaray et al., 2015). In a study carried out by Scholefield et al. (1993) in England using intact montane grassland soil cores in a lysimeter study it has been found that a halfing N fertilization from 400 to 200 kg N $ha^{-1}yr^{-1}$ reduced nitrogen leaching rates from 133.8 to 38.5 kg N $ha^{-1}yr^{-1}$, i.e. approx. a quarter, and decreased peak nitrogen concentration from 55 mg N l^{-1} to 12 mg N l^{-1}. However, other studies using comparable high fertilization rates, came to different results, most likely to differences in soil and climatic conditions. E.g. while applying farm fertilizer up to170 kg N ha^{-1} yr^{-1}, annual leaching rates varied between 10.3 and 17.3 kg N ha^{-1} in cutting grassland of Northern Europe (Bechmann, 2014; Richards et al., 2015) and grazing grassland of Chile (Salazar et al., 2011). In contrast, comparable farm fertilizer application rates resulted in 89.0 kg N $ha^{-1}yr^{-1}$ leaching losses in a study on the Azores with permanent pasture on volcanic soils (Fontes et al., 2011). Nitrogen leaching in the above mentioded studies were mainly nitrate (constituted 71–99% of total nitrogen leaching losses), whilst dissolved organic nitrogen (DON) was the dominant (constituted 59%–84% of total nitrogen) N compound being leached from grasslands in New Zealand and Ireland (Dodd et al., 2014; Ghani et al., 2010; Necpalova et al., 2012). DON concentrations in leachate (0.2–3.5 mg N l^{-1}) are widely reported, yet the ecological consequences and its role in the N cycle of grassland ecosystems are still not well understood (Farrell et al., 2011; Long et al., 2015; McGovern et al., 2014; van Kessel et al., 2009). Although ammonium concentrations in soil water are generally lower (~1 mg N l^{-1}) and it is less subject to leaching (Mian et al., 2009; Necpalova et al., 2012), nitrification can still convert the downward moving ammonium into nitrate, and indirectly contribute to nitrate leaching (Riaz et al., 2008).

Soil heterogeneity and the pronounced spatial variability of climatic conditions on small scales make it difficult to predict nitrogen leaching losses from montane grasslands. For *in situ* ecosystem studies, soil temperature and soil moisture played central roles in driving different nitrogen transformation processes of the grassland N cycle (Wang et al., 2016). Soil temperature was the main controlling factor of mineralisation, yet nitrification and denitrification were largely controlled by soil aeration and thus soil moisture conditions (Beier et al., 2008; Emmett et al., 2004). While the impact of temperature and water supply on individual biogeochemical processes has been widely studied (Butterbach-Bahl et al., 2013), their overall effect on nitrogen leaching are less obvious. In a study involving grassland soils in the USA increasing precipitation was found to result in 11–80 times higher nitrogen leaching rates (Yano et al., 2015), while such an effect was not found in a study in New Zealand (Di et al., 2009). Moreover, as a result of increased plant N uptake nitrogen leaching rates have been found to decrease with increasing temperature (Ineson et al., 1998); or no obvious changes were found since increased soil N availability, and thus increased risk for soil N leaching, was compensated by a decrease in percolation rates (Schmidt et al., 2004). Considering five different climatic years, due to the suppression of net N mineralization, decreased rates of nitrogen leaching were found under conditions of simultaneously declining precipitation and air temperature in Norway (Korsaeth et al., 2003).

As transport medium, soil water percolation largely determines the leaching of C and N compounds. In contrast to soil nitrate concentration, variations in the amount of leaching water explained the observed variations of total nitrogen loss of grasslands in Norway (Bechmann, 2014). Nevertheless, it has been documented that under grazing and application of slurries, soluble soil N content (0.01–59.6 kg ha^{-1}) was positively correlated with gravimetric soil moisture content (Necpálová et al., 2013). Most studies also suggest that weather conditions not only influence soil N turnover processes and soil water movements, but that weather conditions also affect quantities and forms of nitrogen leaching at a given site.

Although it is well established that N availability and soil water flows are major drivers for N leaching losses, the role of plants as sinks for nitrogen and of the soil microbial community as driver of soil N conversions has been stressed widely too (Cameron et al., 1996; Emmett et al., 2004; Jarvis, 2007; Korsaeth et al., 2003; Lin et al., 2010). E.g. increased soil N availability might result in increased evapotranspiration and decreased soil moisture as plant growth is promoted (Wang et al., 2012). Even though water, nitrogen and vegetation dynamics are interacting factors, its interplay is not well understood in grassland ecosystems (Harpole et al., 2007; Niu et al., 2009; Reichmann et al., 2013; Sun et al., 2015).

This study is to our knowledge the first which investigates simultaneously impacts of climate and management on grassland water balance, soil water content and soil temperature, plant growth as well as nitrogen leaching for three different grassland ecosystems along a climate gradient in the Bavarian Alps. The main objectives were: (1) to characterize the magnitude and temporal dynamics of water fluxes, soil nutrient concentrations and leaching losses from extensively and intensively managed grasslands under varying climatic conditions and, (2) to quantify the contribution of different forms of nitrogen (NO_3, NH_4, DON) and DOC to overall leaching losses.

2. Material and methods

2.1. Study area, instrumental setup and experimental design

The study was carried out at three different sites along an elevation, and thus, climatic gradient, E600 (47.82N, 11.06E, 600 m a.s.l.), E770 (47.70N, 10.98E, 770 m a.s.l.), and E860 (46.56N, 11.03E, 860 m a.s.l.), in the Bavarian Alps. Sites are part of the TERENO (Terrestrial Environmental Observations) observatory in S-Germany, funded by the Helmholtz-Society. Based on three years data (2012–2014), from on-site weather stations annual precipitation was 1398 mm, 1121 mm and 1033 mm and mean annual air temperature was 6.5 °C, 8.4 °C and 8.6 °C for E860, E770 and E600, respectively.

At all three elevations a total of six large intact soil cores (stainless steel lysimeter: 1 m^2, 1.4 m height) were excavated without soil and plant disturbances (Pütz et al., 2016) at three replicated grassland sites (1–5 km distance) and transferred to the central sites E860, E770, E600. Lysimeters were operated since mid to end of 2011 and organized in sets of 6 lysimeters placed around a service unit hosting all steering and data recording devices. Lysimeters are closed at the bottom but water can leave or enter the lysimeter via 6 parallel suction cups installed at 140 cm soil depth. Depending on differences between the measured soil matric potential (Tensiometer TS1, METER GROUP, Germany) inside the lysimeter and at the same depth (140 cm) outside the lysimeter at three undisturbed reference plots, water flows either out of the lysimeter into a weighable water tank (psi lysimeter > psi reference) or out of the water tank into the lysimeter (psi lysimeter < psi reference).

Rates of water balance components, i.e. precipitation (P), actual evapotranspiration (ETa) and seepage water (R), are derived from