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Time matters for plant diversity effects on nitrate leaching from temperate grassland

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ABSTRACT

In biodiversity-ecosystem functioning experiments, plant diversity increases biomass production mainly because of complementary resource use. We determined the influence of seasonality and time since conversion from fertilized arable land to unfertilized grassland on the plant diversity-nitrate leaching relationship. NO_3-N concentrations in soil solution, water contents in the main rooting zone, and climate data were measured between 2003 and 2006 in a grassland plant diversity experiment in Jena, Germany which consists of 82 plots with 1–60 plant species and 1–4 plant functional groups (legumes, grasses, non-leguminous tall herbs, and non-leguminous small herbs). To cope with data gaps and uneven sampling intervals, water contents were simulated with Bayesian statistical models, based on the measured data. Downward water fluxes were modeled with a deterministic water balance model. Monthly NO_3-N fluxes were calculated as NO_3-N concentration times downward water flux and statistically analyzed. The statistical results were confirmed with the help of a completely simulated NO_3-N leaching data set without any data gaps. Plant species richness quantitatively decreased NO_3-N leaching in winter, when leaching was highest, more than in summer. The presence of legumes increased and the presence of grasses decreased NO_3-N leaching. The presence of small herbs decreased NO_3-N leaching and this effect strengthened with time. We conclude that especially shortly after land-use change from fertilized arable land to unfertilized grassland, NO_3-N leaching can be reduced if species-rich mixtures without legumes are established.

1. Introduction

Nitrate leaching represents a resource loss and can threaten drinking water quality. Nitrate concentrations in soil solution and nitrate leaching depend on the relation between uptake by plants and soil organisms, atmospheric N_2 fixation, N mineralization (ammonification and nitrification), N deposition from the atmosphere, denitrification, and volatilization (Corre et al., 2002; Schimel and Bennett, 2004). Leaching of nitrate from soil is mainly driven by land-use type, management (e.g., fertilization), land-use change, climate, and soil properties (Dijkstra et al., 2007; Lilburne and Webb, 2002; Perego et al., 2012; Schilling and Spooner, 2006; Strebel et al., 1989). In biodiversity-ecosystem functioning experiments, plant species richness and functional composition of plant communities were shown to positively influence many ecosystem functions such as biomass production and use of resources including N, the quantitatively most important plant nutrient (Allan et al., 2013; Hawkesford et al., 2012; Hooper et al., 2005; Loreau et al., 2001; Niklaus et al., 2006; Spehn et al., 2005; Tilman et al., 1996).

Plant-available nitrate concentrations in soil are one essential component of nitrate leaching that decreases with increasing species richness (Dijkstra et al., 2007; Leimer et al., 2014b; Oelmann et al., 2007c; Tilman et al., 1996). This species richness effect can be explained by a more exhaustive plant uptake because of complementary resource use, irrespective of the functional composition of the plant communities (Niklaus et al., 2001; Tilman et al., 1996). "Complementarity effects" comprise processes like niche differentiation and facilitation which increase the performance of diverse mixtures. On the other hand, "sampling effects" can arise in biodiversity experiments if the probability that dominating species are present increases in species-rich mixtures (Loreau et al., 2001). Plant functional composition and the presence of

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specific plant functional groups possibly affect nitrate concentrations even stronger than species richness (Hooper and Vitousek, 1998; Scherer-Lorenzen et al., 2003; Tilman et al., 1997).

Together with nitrate concentrations in soil solution, downward water fluxes control nitrate leaching. Leimer et al. (2014a) reported for an experimental grassland in Germany smaller downward water fluxes from the 0–0.3 m soil layer on plots containing grasses and larger downward water fluxes on plots containing legumes. Species or functional group richness did not significantly affect downward water fluxes from the 0–0.3 m soil layer (Leimer et al., 2014a). However, in the literature, results regarding plant diversity effects on the water cycle are inconsistent because the effects of species richness and functional group richness on the water cycle vary with the considered soil depth, temporal resolution, and meteorological conditions (Leimer et al., 2014a; Verheyen et al., 2008).

As the product of nitrate concentrations in soil solution and downward water fluxes, nitrate leaching from soil was reported to decrease with increasing species richness (Bingham and Biondini, 2011; Dijkstra et al., 2007; Scherer-Lorenzen et al., 2003). However, in the study of Scherer-Lorenzen et al. (2003), this was only true for mixtures containing legumes, likely because of the experimental design in which the percentage of legume species decreased with increasing species richness (Scherer-Lorenzen et al., 2003). The studies of Hooper and Vitousek (1998) and Oelmann et al. (2007b) did not detect an effect of increasing species richness on nitrate leaching. Besides species richness, plant functional group richness or functional identity could also influence nitrate leaching. Bingham and Biondini (2011) reported decreasing nitrate leaching with increasing functional group richness, but the study of Hooper and Vitousek (1998) showed no functional group richness effect. In general, the presence of legumes tends to increase nitrate leaching because of their N_2-fixing ability (Dijkstra et al., 2007; Hooper and Vitousek, 1998; Scherer-Lorenzen et al., 2003). Grasses might decrease nitrate leaching because of their extensive rooting system (Hooper and Vitousek, 1998) which allows for more exhaustive resource use and therefore reduces both components of nitrate leaching, nitrate concentrations in soil solution (Leimer et al., 2014b; Oelmann et al., 2007c; Scherer-Lorenzen et al., 2003) and downward water fluxes (Leimer et al., 2014a). This is supported by the finding that nitrate leaching decreased with increasing fine root biomass (Scherer-Lorenzen et al., 2003). However, nitrate leaching increased with increasing biomass of C_3 grasses in a fertilized C_4-dominated temperate grassland ecosystem (Bingham and Biondini, 2011). Climatically-induced seasonal variations in the effects of specific functional groups could possibly explain differing results for plant diversity effects on nitrate leaching (Hooper and Vitousek, 1998; Scherer-Lorenzen et al., 2003). To our knowledge, previous studies of plant diversity effects on nitrate leaching used either anion exchange resin bags buried in soil over one vegetation period, a continuous time series of soil solution data of 4–12 months, or 8 soil solution samples distributed over 48 months. It is necessary to increase both the temporal resolution and duration of the observation period to elucidate seasonality or dependence on meteorological conditions of plant diversity effects on nitrate leaching.

The establishment of manipulative diversity experiments usually implies a land-use change from arable to grassland. Arable land usually is fertilized which constitutes a nutrient input into the system and often causes increased nitrate leaching (Christian and Riche, 1998; Dijkstra et al., 2007; Gu et al., 2009; Perego et al., 2012). By mowing and subsequent removal of the biomass, nutrients are removed from grassland ecosystems. In the transition phase after land-use change, the former land use can still affect ecosystem variables like nitrate leaching from the new system for several years (Christian and Riche, 1998; Oelmann et al., 2007c; Schilling and Spooner, 2006). Plant-available N from former fertilization decreases through plant uptake and leaching shortly after establishment of the new system (Christian and Riche, 1998; Leimer et al., 2014b). Later, increasing organic matter concentrations, particularly in the more species-rich mixtures (Steinbeiss et al., 2008), presumably result in enhanced ammonium release (Oelmann et al., 2011) which supplies additional substrate for nitrification. Subsequently, nitrate concentrations in soil solution increase again (Leimer et al., 2014b). Furthermore, plant diversity effects on nitrate leaching might change with time since last fertilizer application because of a progressive decline in fertilizer-derived plant available N. This is supported by Dijkstra et al. (2007), who reported that leaching of dissolved inorganic N from grassland monocultures and 16-species mixtures differed even more if inorganic N fertilizer was applied. Up to now, possible changes in plant diversity effects on nitrate leaching with time after land-use change have, to our knowledge, not been investigated in any study.

The main objective of our study was to investigate for the first time if the effects of plant diversity on nitrate leaching from grassland vary seasonally (monthly resolution) and with time since conversion from arable land to grassland (in the first 4 years). We hypothesize that (1a) nitrate leaching increases if legumes are present and decreases with increasing species richness, functional group richness, and if grasses are present (irrespective of species or functional group richness). (1b) We expect seasonal variation of these plant diversity effects according to meteorological conditions. We further hypothesize that (2) nitrate leaching and plant diversity effects on nitrate leaching are highest in the first year after conversion of arable land to grassland and lower in the following years because plant uptake and leaching reduce the amount of plant-available nitrate originating from former fertilization.

2. Methods

2.1. Study site

This study was conducted as part of the Jena Experiment (http://www.the-jena-experiment.de/), a grassland plant diversity experiment that addresses the role of biodiversity for element cycling and trophic interactions (Roscher et al., 2004).

The field site is located close to the city of Jena, Germany (50°55′ N, 11°35′ E; 130 m above sea level) on the floodplain of the Saale river. Mean annual air temperature is 9.3 °C and mean annual precipitation is 587 mm (1961–1990; Kluge and Müller-Westermeier, 2000). The soil is an Eutric Fluvisol (IUSS, 2007) that developed from up to 2 m thick loamy fluvial sediments which are almost free of stones. Because of the fluvial dynamics, the texture ranges from sandy loam near the river to silty clay with increasing distance from the river. This systematic variation in soil texture is considered in the experimental design and the plots are therefore arranged in four blocks, parallel to the river Saale. The plots within one block have an approximately homogeneous soil texture. Soil texture, total carbon, inorganic carbon, organic carbon, total nitrogen content, organic C to N ratios (measured in 2002 in the 0–0.3 m soil layer), and pH (H_2O; measured in 2003 in the 0–0.15 m soil layer) per block are given in Table 1. The study site was converted from grassland to an arable field in the 1960s and thus fertilized and plowed for crop production until the beginning of the grassland plant diversity experiment in 2002.

The entire experimental design is described in Roscher et al. (2004). Briefly, the main experiment comprises 82 plots (20 m × 20 m) grouped in 4 blocks. The 82 plots were established from seeds in May 2002 with different levels of species richness (1–60 plant species) and functional group richness (1–4 plant functional groups out of grasses, small herbs, tall herbs, and legumes;