Journal of Environmental Management 165 (2016) 243–252

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Impacts of management and climate change on nitrate leaching in a forested karst area

Thomas Dirnböck [a,*], Johannes Kobler [a], David Kraus [b], Rüdiger Grote [b], Ralf Kiese [b]

[a] Environment Agency Austria, Department for Ecosystem Research and Data Information Management, Spittelauer Lände 5, 1090, Vienna, Austria
[b] Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Kreuzeckbahnstraße 19, 82467, Garmisch-Partenkirchen, Germany

A R T I C L E I N F O

Article history:
Received 14 July 2015
Received in revised form
24 September 2015
Accepted 26 September 2015
Available online 3 October 2015

Keywords:
Ecological modelling
LTER Zöbelboden
Forest growth
Forest clear-cut
Forest management
LandscapeDNDC

A B S T R A C T

Forest management and climate change, directly or indirectly, affect drinking water resources, both in terms of quality and quantity. In this study in the Northern Limestone Alps in Austria we have chosen model calculations (LandscapeDNDC) in order to resolve the complex long-term interactions of management and climate change and their effect on nitrogen dynamics, and the consequences for nitrate leaching from forest soils into the karst groundwater. Our study highlights the dominant role of forest management in controlling nitrate leaching. Both clear-cut and shelterwood-cut disrupt the nitrogen cycle to an extent that causes peak concentrations and high fluxes into the seepage water. While this effect is well known, our modelling approach has revealed additional positive as well as negative impacts of the expected climatic changes on nitrate leaching. First, we show that peak nitrate concentrations during post-cutting periods were elevated under all climate scenarios. The maximal effects of climatic changes on nitrate concentration peaks were 20–24 mg L^{-1} in 2090 with shelterwood or clear-cut management. Second, climate change significantly decreased the cumulative nitrate losses over full forest rotation periods (by 10–20%). The stronger the expected temperature increase and precipitation decrease (in summer), the lesser were the observed nitrate losses. However, mean annual seepage water nitrate concentrations and cumulative nitrate leaching were higher under continuous forest cover management than with shelterwood-cut and clear-cut systems. Watershed management can thus be adapted to climate change by either reducing peak concentrations or long-term loads of nitrate in the karst groundwater.

1. Introduction

Although karst aquifers support a quarter of the world's population with drinking water, only a few studies have quantified the impact of climate change on these resources (Hartmann et al., 2014). Though nitrate pollution of drinking water is usually attributed to the fertilization of crops and grassland, an excess input of atmospheric nitrogen from industry, traffic and agriculture into forests has also caused considerable nitrate losses in forest areas across Europe (Butterbach-Bahl and Gundersen, 2011; Erisman and de Vries, 2000; Gundersen et al., 2006; Kiese et al., 2011). Such losses are also to be expected in the Northern Limestone Alps area which is exposed to particularly high nitrogen deposition (Rogora et al., 2006). It is expected that climate change will affect nitrogen loss because leaching is tightly linked to precipitation (Kane et al., 2008) and to the retention capacity of the respective forest ecosystems (Jost et al., 2011).

Apart from nitrogen deposition and climate change, forest management exerts impacts on karst water resources, both in terms of quality and quantity. When managed appropriately, the fragile soil and humus horizons which are essential for water retention and nitrogen filtering can be kept stable (Christophel et al., 2013) and thus can contribute to a low level of water pollution (Katzensteiner, 2003; Weis et al., 2006). Tree harvest exerts strong control over nitrogen cycling but also over the loss or accumulation of soil organic matter (Brevik et al., 2015; Butterbach-Bahl and Gundersen, 2011; van Groeningen et al., 2015). Clear-cuts and shelterwood-cuts, which are commonly applied in order to maximize the production of merchantable wood, often lead to soil degradation causing severe nutrient and humus losses as well as a

* Corresponding author.
E-mail address: thomas.dirnboeck@umweltbundesamt.at (T. Dirnböck).

http://dx.doi.org/10.1016/j.jenvman.2015.09.039
0301-4797/

partial loss of the soil functions (Christophel et al., 2013; Katzensteiner, 2003). Due to such management, the nutrient cycle can be disrupted so that if nitrate is available, it is mobilized and washed out from the soils, typically within a few years after the event (Gundersen et al., 2006; Katzensteiner, 2003; Weis et al., 2006).

While extensive knowledge exists as to the effects of forest management on nitrate leaching (Gundersen et al., 2006; Jerabkova et al., 2006), interactions with the impacts of climate change remain rather obscure (Bernal et al., 2012). For the Northern Limestone Alps area, downscaled A1B, A2 and B2 scenarios predict a temperatures increase in the range of 2–5 °C by the year 2100 (IPCC, 2013), with stronger increases likely in the summer months. Precipitation is assumed to increase in winter and decrease in summer (Ahrens et al., 2014; Loibl et al., 2011). Since nitrate leaching depends on the amount of seepage water (Jost et al., 2011; Kane et al., 2008), less precipitation and higher temperatures and thus higher evapotranspiration during summer should decrease the leaching rates. However, higher temperatures may also affect tree growth and thus nitrogen uptake in different ways. Rising temperatures in the past have led to an increase in tree growth in Europe (Pretzsch et al., 2014) but in the future, drought effects may counteract this positive trend (Charru et al., 2014; Hartl-Meier et al., 2014a; Lindner et al., 2010). Last but not least, temperature and soil moisture exert direct control over N mineralization, nitrification and the soil N cycle in general (Butterbach-Bahl and Gundersen, 2011; van Groeningen et al., 2015).

We studied the interactions of climate change and forest management in an intensively monitored Long-Term Ecosystem Research (LTER) site in the "Kalkalpen" national park (LTER Zöbelboden). Therefore we applied a physiologically oriented ecosystem model with a detailed soil process description (LandscapeDNDC) (Haas et al., 2013) in order to examine the complex long-term interactions of forest management and climate change and their impact on tree growth and nitrogen dynamics. Complemented by common management routines (Grote et al., 2011b), the model was used here for exploring tree growth and nitrogen leaching over entire rotation periods under future climate conditions. We tested specifically the following hypotheses associated with climate change.

1) An increase in temperature will stimulate tree growth, leading to a higher nitrogen uptake and less nitrate concentrations in seepage. We expect an interaction between forest management and climate change because tree growth is controlled by management.
2) After a clear-cut nitrate leaching will be higher under climate change owing to the combined effect of more available N and increased nitrogen turnover in the soil.
3) The nitrate load in the groundwater will be reduced over the entire rotation period because changes in precipitation and evapotranspiration will cause lower groundwater recharge. Again, forest management will interfere with climate change owing to the role of the trees in controlling water percolation.

2. Materials and methods

2.1. Study area

The studied forest stand was located within the Austrian LTER site "Zöbelboden" in the northern part of the "Kalkalpen" national park in Austria (N 47°50′30″, E 14°26′30″). The long-term average annual air temperature was 7.8 °C (1996–2011). The mean annual rainfall between 1996 and 2011 was 1645 mm. Snow cover (>10 cm) lasted from December to April. The mean N deposition in the bulk precipitation between 1993 and 2006 was 18.7 kg N ha^{-1} yr^{-1}, of which 15.3 kg were inorganic nitrogen (approximately half NO_3^--N and half NH_4^+-N) (Jost et al., 2011). The one hectare study site (intensive plot 1, IP 1) is located on an almost flat plateau at ~ 950 m.a.s.l where Chromic Cambisols predominate with patches of Rendzic Leptosols and Hydromorphic Stagnosols. The mineral soil is an A_h-AB-B silty clay or silty loam with bedrock found at a depth of around 50 cm (see also Table 1). The pH value is 5.3 in the humus layer and around 6.5 in the mineral soil. Total soil carbon stocks including litter are 115 tons C ha^{-1} (Kobler et al., 2015). The C/N ratio is around 27 in the humus layer and 17 in the upper 10 cm of the mineral soil (Jost et al., 2011). Mull and moder humus forms predominate. The plot is dominated by Norway spruce (*Picea abies* Karst.) planted after a clear-cut around the year 1910. Spruce has a standing volume of 860 m^3 ha^{-1} and European beech (*Fagus sylvatica* L.) 114 m^3 ha^{-1}.

2.2. The LandscapeDNDC model

LandscapeDNDC is a modular ecosystem model that combines detailed soil process representations with physiologically-oriented vegetation description. It is suitable for simulating total ecosystem C and N balances as well as associated changes in the C and N stocks of soils for forest, arable, and grassland ecosystems (Haas et al., 2013). A particularly strong point of the model is its detailed description of the nitrogen balance, including trace gas emission and leaching (Cameron et al., 2013). This description is based on the integration of physical, biogeochemical, and hydrological processes that are taken from the agricultural DNDC model (Li et al., 1992) and the Forest-DNDC model (Li et al., 2000). In its previous form, LandscapeDNDC was evaluated to represent the water balance of a forest under different weather conditions (Holst et al., 2010) and used successfully to model nitrate leaching for all forest sites in Germany (Kiese et al., 2011). For the current analysis, we have used a more detailed forest ecosystem model within LandscapeDNDC which combines a high sensitivity to environmental changes based on physiological processes (Grote et al., 2009) with a realistic description of dimensional forest development (Grote et al., 2011a). It is also able to represent different species and different size classes of a species at a particular site (Grote et al., 2011b).

2.3. Data acquisition

Climatic variables (i.e. air temperature, precipitation, vapor pressure deficit, solar radiation) have been recorded at half-hourly intervals at a field climate station in close vicinity to the experimental stand since the year 1993 and at a measuring tower with a height of 40 m, also in close vicinity. Gap filling with missing data was done according to Jost et al. (2011).

Total N, nitrate and ammonia in bulk precipitation, throughfall, and seepage from the soil-bedrock interface into the karst system have been monitored since 1993. Samples used to be analysed at weekly intervals until 1999. From 1999 onwards, samples from two consecutive weeks were combined (volume weighted) and since 2008 sampling has been carried out every four weeks. For more details see Jost et al. (2011).

Forest stand inventories were conducted in 2003, 2007 and 2012 including measurements of tree position, tree height and diameter at breast height (dbh; 1.37 m). The number of individuals per tree species, as well as the mean tree and crown height, and the mean dbh were used to derive forest biomass and structure for model initialisation (Table 1). Annual aboveground tree biomass data of the studied stand was taken from Kobler et al. (2015). Soil characteristics which came from a soil inventory in the year 2012