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Assessing the impact of changes in land-use intensity and climate on simulated trade-offs between crop yield and nitrogen leaching

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ABSTRACT

In this study, a global vegetation model (LPJ-GUESS) is forced with spatial information (Nomenclature of Units for Territorial Statistics (NUTS) 2 level) of land-use intensity change in the form of nitrogen (N) fertilization derived from a model chain which informed the Common Agricultural Policy Regionalized Impact (CAPRI) model. We analysed the combined role of climate change and land-use intensity change for trade-offs between agricultural yield and N leaching in the European Union under two plausible scenarios up until 2040. Furthermore, we assessed both driver importance and uncertainty in future trends based on an alternative land-use intensity dataset derived from an integrated assessment model. LPJ-GUESS simulated an increase in wheat and maize yield but also N leaching for most regions when driven by changes in land-use intensity and climate under RCP 8.5. Under RCP 4.5, N leaching is reduced in 53% of the regions while there is a trade-off in crop productivity. The most important factors influencing yield were CO_2 (wheat) and climate (maize), but N application almost equaled these in importance. For N leaching, N application was the most important factor, followed by climate. Therefore, using a constant N application dataset in the absence of future projections has a substantial effect on simulated ecosystem responses, especially for maize yield and N leaching. This study is a first assessment of future N leaching and yield responses based on projections of climate and land-use intensity. It further highlights the importance of accounting for changes in future N applications and land-use intensity in general when evaluating environmental impacts over long time periods.

1. Introduction

Modern agriculture and forestry have transformed a large proportion of the planet's land surface so that only one fifth of the global ice-free surface remains unmanaged by humans (Ellis and Ramankutty, 2008; Erb et al., 2007). Agricultural ecosystems (croplands and pastures) have become one of the largest terrestrial biomes on the planet, comparable to forest cover in extent and occupying approximately 40% of the land surface (Foley et al., 2005; Ramankutty et al., 2008). Since the character of land-use varies greatly across the world, land-use intensity becomes a critical characteristic of managed land systems (Foley et al., 2007; Asselen and Verburg, 2012). Land-use intensity is typically conceptualized as the degree of yield amplification caused by human activities and measured with the use of input–output analyses and by quantifying changes in system properties, e.g., in the amount of fertilizer applied, the number of pesticide applications, the density of livestock units or field sizes (Erb et al., 2013; Plieninger et al., 2015). Land-use intensity is important to consider when studying managed landscapes since most processes that transform landscapes occur along gradients of land-use intensity (Rounsevell et al., 2012; Kuemmerle et al., 2013). Land-use intensity is distributed unevenly, as demonstrated for example in Europe, in the intensity of forest harvesting measured via harvested timber volumes (Levers et al., 2014) and grazing intensity derived from livestock density (Neumann et al., 2009, 2011).

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The projected future growth of the human population, by 2050, is estimated to be between 8.3 billion and 10.9 billion (United Nations, 2013) and coupled with an increase in affluence and consumption in developing and emerging economies, will increase the demand for food, fiber and fuel throughout the next decades (Godfray et al., 2010). Therefore, the per capita food consumption is expected to increase from a global average of 2800 kcal per day in 1999–2001 to 3100 kcal per day in 2050 (Food, Agriculture Organization (FAO), 2004). As a consequence of these predictions, food production may need to double by 2050 (relative to 2005 levels), to meet the increased demand (Eitelberg et al., 2015). Since most of the fertile land on earth is already used and opportunities for expansion are being exhausted, human society will have to rely on an increase of output per unit area in agriculture and forestry rather than on the expansion of managed land (Ellis and Ramankutty, 2008; Erb et al., 2007; Foley et al., 2011). Industrial fixation of nitrogen (N), for instance, is projected to be 165 Tg/year by 2050 compared to 100 Tg/year in 2000 (Galloway et al., 2004). Much of the projected increase in fertilizer use is expected to occur in developing nations. However, an increase in land-use intensity will often negatively impact the environment and the provisioning of other ecosystem services besides food production. Intensively used agricultural systems are often N-saturated (Chapin et al., 2011) and the augmented use of fertilizer increases the leaching of N into aquifers and aquatic ecosystems and thus carries costs to environmental services such as water quality. This relationship between fertilizer loading and nitrate leaching is often linear for wheat and maize systems (Zhou and Butterbach-Bahl, 2014), although some studies have reported an exponential pattern for maize (e.g. Wachendorf et al., 2006). This requires balancing agroecosystem services (such as food provision) and dis-services (such as N leaching). Sustainable intensification is needed which aims for the production of more food, feed, fiber and fuel on the same, or even a reduced, area of land while at the same time minimizing the environmental impacts.

Hence, in order to effectively examine and project the negative effects of increasingly intensified agricultural systems on the environment, land-use intensity and livestock information are important variables to use in addition to land cover composition in global land classification. While land-use and land cover maps and models exist, one major challenge which remains is the step from land-use and land cover change (LULCC) projections to land-use intensity and projections in changes therein. Despite the importance of land-use intensity and changes in land-use intensity, spatially explicit data and models are scarce for Europe, particularly at a detailed resolution. This is partly due to a lack of homogeneous datasets, modeling, monitoring and mapping strategies. Since it is known that not only changes in agricultural policy, but also changing market conditions and demand affect the intensity of agricultural land-use, these elements must be included in the development of a method to map the current spatial distribution of agricultural intensity and predict the future (agricultural) policy effects on agricultural intensity (Temme and Verburg, 2011).

A few studies have been conducted in the context of current N application as an element of land-use intensity: Zaehle et al. (2010a) developed and used a global absolute N application dataset for cropland and historical time periods ranging from 1910 to 2005, on a medium spatial resolution of 0.5°. Their dataset is based on country-wise ammonium plus nitrate data from the FAO statistical database (1960–2005). It was extended in time for the years 1910–1960, assuming an exponential increase. Potter et al. (2010) calculated fertilizer input maps of N and phosphorus by combining national-level statistics on fertilizer use with maps of global harvested area for 175 crops. Mueller et al. (2012) developed a crop-specific dataset of nitrogenous fertilizer application for 138 crops, centered on the year 2000, by spatially disaggregating both national and sub-national data from a variety of sources (e.g. FAO, fertilizer research institutes, national statistical bureaus). Elliott et al. (2014) used N-fertilizer information from the AgGRID dataset which provides long-term mean N fertilizer input centered on the year 2000, based on national statistics from the FAO.

However, very few studies model changes in N application for future time periods. Stocker et al. (2013) applied a process-based model to reproduce both historical and scenario-based atmospheric nitrous oxide (N_2O) and methane (CH_4) budgets. In their study, they expanded the dataset from Zaehle et al. (2010a) and included simulated future fertilizer applications from the integrated assessment model MESSAGE for Representative Concentration Pathways (RCP) 2.6 and 8.5 (Bouwman et al., 2013; Riahi et al., 2011). The study uses absolute N application per gridcell and does not discern between different crop types.

In this study, a dynamic global vegetation model (DGVM) LPJ-GUESS (Smith et al., 2001) is forced with spatially explicit, crop specific and detailed information (NUTS 2 (Nomenclature of Units for Territorial Statistics) level) of both land-use intensity and land-use intensity change to analyze trade-offs between yield and N leaching for Europe. Here, agricultural land-use intensity is defined in terms of mineral N fertilizer input. We aim to answer the following questions:

1 What are the combined impacts of changes in climate, CO_2 concentration and land-use intensity on projections of yield and N leaching in Europe?
2 What are the quantitative contributions of the drivers climate, CO_2 and land-use intensity for projections of yield and N leaching? What are the implications of using a constant land-use intensity dataset in the absence of future trajectories?
3 To what extent does the modeling chain behind the N application trajectories affect the projected trends of yield and leaching simulated by LPJ-GUESS?

The latter research question is tackled by using an alternative dataset in order to provide some notion of uncertainty in projected N application rates. In summary, the goal of this study is twofold. Firstly, we aim to project trade-offs between yield and N leaching for Europe up until 2040 and discuss their implications for adaption planning. Secondly, we aim to provide information about the sensitivity of a biogeochemical model (here LPJ-GUESS) to land-use intensity change information in the form of N fertilization and assess its importance for future simulations. Although we are evaluating the sensitivity using one model only, we expect our results to be representative for a wide range of biogeochemical models, given the similarity in their process representation (e.g. soil carbon (C) and N dynamics, that are based on the CENTURY model (Parton et al., 1993)).

2. Method and materials

In this study, nitrogen projections derived from a top-down modeling framework have been combined with climate projections as simulated by five general circulation models (GCMs) to inform the process-based ecosystem model LPJ-GUESS and simulate trade-offs between crop yield and N leaching (see Fig. 1).

2.1. Models

2.1.1. LPJ-GUESS

LPJ-GUESS is a well-established, process-based ecosystem model designed for regional to global applications. The present study uses the land-use and crop module of LPJ-GUESS (Lindeskog et al., 2013; Olin et al., 2015a,b) which is based on approaches by