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Evaluating the impacts of climate change and crop land use change on streamflow, nitrates and phosphorus: A modeling study in Bavaria

B. Mehdi[a,*], R. Ludwig[b], B. Lehner[a]

[a] Department of Geography, McGill University, 805 Sherbrooke Street West, Montreal, QC H3A 0B9, Canada
[b] Department of Geography, Ludwig Maximilians University, Luisenstrasse 37, 80333 Munich, Germany

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ABSTRACT

Study region: Bavaria, Germany.
Study focus: The Altmühl River is prone to nutrient inputs from agricultural activities. Quantifying nitrate nitrogen ($NO_3{}^-$-N) and total phosphorus (TP) concentrations due to potential future changes in the watershed is necessary for managing water quality and adhering to water policy directives. The Soil and Water Assessment Tool (SWAT) was used to provide stakeholders with support in determining the impacts of climate change (CC) in combination with crop land use change (LUC) scenarios on streamflow, $NO_3{}^-$-N and TP to the 2050 time horizon. The CC simulations stemmed from RCMs and the LUC scenarios were developed with stakeholders.
New hydrological insights for the region: When CC was combined with LUC, mean annual $NO_3{}^-$-N loads increased 3-fold, and TP loads 8-fold, compared to the CC simulations alone. Nutrient loads were higher in several months due to the future increased annual precipitation plus the additional fertilizer input in the land use scenarios. The maize areas above the Altmühl Lake contributed greatly to TP loads, while winter wheat areas mainly contributed to $NO_3{}^-$-N loads. When CC was combined with LUC, the in-stream nutrient concentrations exceeded ministerial guidelines of 11 mg TP/L and 0.05 mg$NO_3{}^-$-N/L every month at the outlet. CC simulations combined with LUC scenarios demonstrated non-linear dynamics whereby the direction and the magnitude of impacts were not predictable from the individual changes alone.

* Corresponding author. Current address: Universität für Bodenkultur, IWHW, Muthgasse 18, 1190 Wien, Austria. Tel.: +43 660 571 6178.
E-mail address: bano.mehdi@mail.mcgill.ca (B. Mehdi).

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1. Introduction

Protecting and restoring aquatic ecosystems is a priority in Europe that has been formalized by the European Water Framework Directive (2000/60/EC) (EC, 2000). The Water Framework Directive (WFD) aims to maintain and improve the aquatic environment partly by ensuring a good water quality status through the implementation of river basin management plans (RBMPs). A recent report by the European Commission (EC, 2012) indicated that over 90% of RBMPs mentioned agriculture to be a significant pressure in their basin by contributing, for example, to excess organic matter, nutrients and pesticides. Farm management practices are an integral part of RBMPs because numerous field operations, such as fertilizer management, can address non-point source pollution (Cherry et al., 2008).

In basins where agricultural activities dominate, it is common for the quality of water to be compromised (Green et al., 2014; Patoine et al., 2012; Volk et al., 2009). For example, in Denmark, Nielsen et al. (2012) found a high correlation between the amount of agricultural land and the total nitrogen (N) and total phosphorus (TP) concentrations in adjacent lakes. Donner (2003) determined the area of maize in the U.S. to be strongly correlated to N loads, and to a lesser extent to phosphorus (P).

The mineral forms of N that are most readily available for plant uptake are nitrate (NO_3^-) and ammonium (NH_4^+) (Batlle-Aguilar et al., 2011) and therefore these are commonly applied as fertilizer ammendements. When soil temperatures exceed 5 °C, NH_4^+ is readily adsorbed onto clay minerals or assimilated by microorganism and plants, or it is transformed into ammonia gas (NH_3), therefore NH_4^+ is not prone to movement. Nitrate on the other hand is highly soluble and easily transported by hydrological flow pathways such as leaching, throughflow or deep percolation (Lapp et al., 1998).

Phosphorus is another essential plant macronutrient which is often not present in sufficient available forms in the soil for optimum crop growth requirements. In the soil, P combines with other ions to form insoluble compounds that can precipitate out of solution. This characteristic allows P to be available for transport, primarily by surface runoff (Michaud and Laverdière, 2004). Soluble forms of P that are plant available are the inorganic forms known as orthophosphates ($H_2PO_4^-$ or HPO_4^{2-}). These forms are mobile, and can be transported by diffusion or by surface water flow into field drains, but they are easily adsorbed to clay particles or immobilized by organic matter and therefore are limited to the upper soil layers (Hillel, 1982).

Surface water quality can be improved through implementing "best" agricultural practices, as demonstrated by research in Bavaria (Germany) where agricultural field practices were switched from being intensive to sustainable (including intercropping, hedges, terraces, retention basins, buffer strips and changing arable land to fallow). These reduced N loads by up to 50% and phosphate loads by up to 25% in the adjacent stream after 4 years (Honisch et al., 2002). However, cleanup efforts at the larger scale may only show results after a few decades. A study examining NO_3^- and NO_2^- changes in Iowa (U.S.) from 1970 to 2012 suggested long-term N transport in watersheds due to fertilizer inputs on maize (Green et al., 2014).

Since agricultural land can have such a variety of effects on water quality, investigating potential land use and management changes in a basin is necessary to achieve the WFD objectives which will be evaluated during planning cycles ending in 2015, 2021 and 2027.

Land use evolves continuously; in Western Europe, the two greatest changes from 1950 to 2010 were the conversion of grassland to forest, as well as the transition of cropland to grassland (Fuchs et al., 2013). In Europe, agricultural land has decreased in overall area, yet at the sub-regional level disparities exist. For example, in Upper Franconia (Germany) the tilled areas since 1960 have increased at the expense of wooded areas due to arable land being in high demand; mostly because crop farms needed to expand to maintain economic viability. Concurrently, farming was intensified on productive land, driven by specialized livestock farming (Bender et al., 2005). The intensification of agriculture appears in several projections of land use for Germany (e.g. Henseler et al., 2008). Germany's energy transition policy that aims to increase the amount of renewable energy sources will also be a strong driver to increase biomass for biofuel production on agricultural land (Schorling et al., 2014).

At the same time, climate change will affect crop growth and bring changes to the growing season. In Germany, from 1959 to 2009, mean monthly temperatures during the oat growing season (March–August) increased by approximately 0.3 °C per decade (Siebert and Ewert, 2012). The flowering and maturity of cereals in Europe by 2040 are projected to advance by 1–3 weeks (the greatest