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Modeling the combined effects of changing land cover, climate, and atmospheric deposition on nitrogen transport in the Neuse River Basin☆

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ABSTRACT

Study region: The SWAT model was used to estimate the combined effects of changing land cover, climate and Clean Air Act (CAAA)-related atmospheric nitrogen (N) deposition to watershed nitrogen fate and transport for two watersheds in North Carolina, USA.

Study focus: Two different model simulation scenarios were applied: one included CAAA-related atmospheric N deposition, climate and land cover (CAAD + C + L) and the other only included CAAA-related N deposition (CAAD) in simulation.

New hydrological insights for the region: Results show both scenarios generated overall decreasing trends for nearly all N outputs between 2010 and 2070 which resulted primarily from CAAA-related reductions in oxidized N deposition. In both watersheds, including climate and land cover change in simulation resulted in a relative 30% higher NO3 load, 30% higher denitrification, 10% higher organic N load and a 20% smaller level of plant N uptake in year 2070 compared to not including climate and landcover changes in simulation. The increases in N transport for both watersheds indicates the combined impacts from climate and land cover change may offset benefits provided by the CAAA regulations; however, future NO_3 loads for the Little River watershed were small relative to current N loading rates. Conversely, the increasing NO_3 and organic N loads for the nearby Nahunta watershed were significant compared to current rates demonstrating that watershed nutrient responses to climate and land cover changes may vary significantly over relatively small spatial scales.

1. Introduction

Global climate change is expected to present significant changes to seasonal and long-term variability of surface flows, groundwater flows and water quality. In particular, a greater occurrence of extreme meteorological events is anticipated (Cambell et al., 2009; Ficklin et al., 2010; Johnson et al., 2012; Van Liew et al., 2012; Dayyani et al., 2012, Sellamia et al., 2016). With a steady increase in global population, urban development quickly follows, which also heavily influences watershed hydrology and pollutant load delivery (Ferrier et al., 1995; Sobota et al., 2009; Wilson and Weng 2011; Wiley et al., 2010; Tang et al., 2011; Bosch et al., 2014). Watershed systems are highly sensitive to climate conditions. In many areas, climate change is expected to exacerbate current

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stresses on water resources from population and economic growth, land use change and urbanization (Butcher et al., 2013). A recent report by a committee of business and policy leaders say the US economy could face significant disruptions from climate change. Of particular concern are impacts to ecosystem function and expansion of anoxic regions in oceans that is further confounded by uncertainties inprojected climate change (Showstack, 2014).

Currently, there is a relatively large literature base concerning impacts of climate and land cover change on watershed hydrology and water supply, however water quality and upland biogeochemical responses have been studied much less in this context (Tu, 2009; Han et al., 2009, Kundzewicz, 2010; Park et al., 2010, 2011; Dayyani et al., 2012; Chiang et al., 2012; Johnson et al., 2012; Van Liew et al., 2012; Whitehead and Crossman, 2012, Bussi et al., 2016). Furthermore, few studies have analyzed the combined effects of land cover and climate change on nutrient transport (Bierwagen et al., 2010; Park et al., 2011; Van Liew et al., 2012; Astaraie-Imani et al., 2012, Johnson et al., 2015, Bussi et al., 2016). Water quality responses to changes in climate are difficult to predict because of complex biogeochemical cycling in aquatic and upland environments (Howarth et al., 2006; Cambell et al., 2009; Bernal et al., 2012). Issues regarding nitrogen transport under climate change involve not only changes in short term delivery but also transformations in landscape nitrogen sinks (storage in soils and biomass or rates of denitrification) (Aber et al., 2002; Howarth et al., 2006). Elevated levels of nitrogen in freshwater systems, estuaries and coastal areas are of concern due to nitrogen's role in water-quality degradation, eutrophication and hypoxia (Smith et al., 1999; Galloway et al., 2004; Compton et al., 2011; Passeport et al., 2012).

Along with climate and land cover, the characteristics of atmospheric nitrogen deposition have a major impact on nitrogen transformation and delivery in watersheds. Atmospheric pollutant composition and concentration is heavily impacted by the type and intensity of industrial emissions. In the US, emissions regulation is enforced under the US Environmental Protection Agency's (USEPA) Clean Air Act (CAA) (1963, 1967, and 1970) and the Clean Air Act Amendments (CAAA) of 1977 and 1990 (U.S. Environmental Protection Agency (USEPA), 1999; Butler et al., 2005). A primary goal of CAAA is to reduce ecosystem damage associated with low pH (acid) deposition in the eastern US and eastern Canada (Butler et al., 2001).

Investigations combining climate, land cover and atmospheric nitrogen deposition change into one modeling framework to evaluate long term projections in ecosystem nutrient dynamics are limited in number and scope (Civerolo et al., 2008; Cambell et al., 2009, Pan et al., 2009; Shi et al., 2011, Bussi et al., 2016), largely because of difficulties in linking various data sources and biogeochemical modeling components. Climate, land cover/use and atmospheric deposition represent primary factors affecting global water quality and nutrient balance (Williamson et al., 2008; Park et al., 2010; Churkina et al., 2010) therefore modeling investigations including these factors could provide a comprehensive evaluation of the broad spectrum of global influence which can lead to more accurate predictions of water quality and better management of natural resources.

A previous study by this research group showed that the decrease in CAAA-related atmospheric nitrogen deposition from 1990 to 2010 over the Neuse River Basin region correlates with a decrease in nitrogen discharges from the Little River and Nahunta watersheds (Gabriel et al., 2014b). In a separate climate and land cover change investigation, Gabriel et al., 2016 separately tested the influence of climate and land cover changes to determine the relative sensitivity of climate and land cover on nitrogen discharges for years 2010–2070. They showed nitrogen watershed discharges increase with increasing ambient CO_2, decrease with land cover urbanization and have a mixed response to precipitation and ambient temperature fluctuations. This study also showed nitrogen watershed discharges were much more sensitive to the combined effects of precipitation and temperature than CO_2 and land cover changes.

The purpose of the study presented here is to further build this recent work by Gabriel et al. by combining climate, land cover and CAAA-related changes in atmospheric nitrogen deposition into one modeling framework to reveal the combined influence of all three on nitrogen fate and transport for these in these two watersheds (Little River and Nahunta in North Carolina, USA). We also ran a series of simulations that do not contain climate and land cover changes; only CAAA-related changes in atmospheric deposition were included. This was completed to determine the relative influence of climate and land cover changes on the system, because over the long term, the benefits of CAAA regulations on nitrogen discharges may be offset or further enhanced with the advancement of climate and land cover changes (Civerolo et al., 2008).

For this study, we once again used the Soil and Water Assessment Tool (SWAT) watershed model for all watershed simulations and extracted output data for nitrogen (NO_3 and organic nitrogen) stream/river discharge, upland denitrification and plant nitrogen uptake. We chose nitrogen discharge, denitrification and plant nitrogen uptake as the response variables because each are primary pathways for watershed nitrogen removal. Nitrogen discharges are a final product of the interaction between upland biogeochemistry, atmosphere-surface exchange, hydrology, land cover change, land management practices and are the focus of many pollution abatement programs, e.g. Total Maximum Daily Loads. Denitrification is a difficult process to experimentally measure as it occurs in small anaerobic pockets in soil and depends on NO_3 availability, carbon availability, temperature and substrate composition (Donner et al., 2004) and can vary dramatically with climate variation (Groffman et al., 2009); therefore, model simulations that provide estimates of denitrification including plant uptake are particularly valuable. The climate data used in this study involves ambient CO_2, precipitation and temperature. CO_2 data were obtained from estimates determined by the International Panel on Climate Change (IPCC) and future estimates for precipitation and temperature were obtained from two statistically downscaled Global Circulation Models (GCMs). Land cover change predictions were obtained from the US Environmental Protection Agencies (USEPA) Integrated Climate and Land Use Change (ICLUS) project and the USEPA's Community Multi-scale Air Quality (CMAQ) model was used to obtain future estimates for atmospheric nitrogen deposition.

The study presented here is essentially a single-scope scenario analysis since we consider one atmospheric deposition projection scenario beyond 2010, one climate and one land use (land cover) change scenario (A2; "business as usual" scenario); therefore, the results presented are one of many possible future outcomes. However, we do examine two extreme climate scenarios (wet-cold and dry-warm) including the predominant projected land cover conversion (agricultural and forested to urban) for the studied region. The

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