Agricultural nutrient loadings to the freshwater environment: the role of climate change and socioeconomic change

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Abstract

Human activities, in particular agricultural production, interfere with natural cycles of nutrient elements, nitrogen (N) and phosphorus (P), leading to growing concerns about water quality degradation related to excessive nutrient loadings. Increases in agricultural production in response to population growth and wealth generation further increase risks associated with nutrient pollution. This paper presents results from projections of nutrient exports from global agricultural crop and pasture systems to the water environment generated using a process-based modeling approach. Brazil, China, India and the United States account for more than half of estimated global N and P loadings in the base year. Each country boasts large agriculture centers where high calculated loading values are found. Rapid growth in global agricultural nutrient loadings is projected. Growth of agricultural pollution loading is fastest in the group of low-income developing countries and loading growth rates also vary substantially with climate change scenario. Counter measures need to be taken to address the environmental risks associated with the projected rapid increase of agricultural nutrient loadings.

1. Introduction

Nitrogen and phosphorus are essential nutrient elements for sustaining life. However, the presence of excess nitrogen and phosphorus in water deteriorates water quality. A consequence of unusual enrichment of nitrogen and phosphorus in aquatic environments is eutrophication. Eutrophication can lead to hypoxia and loss of biodiversity and has become a widespread environmental problem worldwide (Smith 2003). Moreover, nitrogen compounds in drinking water are a threat to human health. The World Health Organization (WHO) recommends 10 mg l\(^{-1}\) as a limit of nitrate-nitrogen in drinking water (WHO 2004). High level of nitrates may cause methemoglobinemia, especially in infants under six months, and is also suspected to be linked with elevated risk of gastric cancer (Ward et al 2005).

While nutrient loadings to the water environment can occur naturally, human activities interfere with nitrogen and phosphorus cycles and have been blamed for intensifying the nutrient loadings to water environment. Among various anthropogenic sources of nutrient pollutants, agriculture is regarded as a major one (Smith et al 1997, Torrent et al 2007, Sun et al 2012). Modern farming practices are characterized by extensive use of inorganic fertilizers. There are also intensified nutrient fluxes arising from livestock production.

The concerns about agriculture nutrient loadings are expected to exacerbate in the future. Changes in socioeconomic drivers will drive up global food demand which, in turn, will lead to further intensification of global agricultural production. The challenge of achieving both environmental sustainability and food security has been well recognized (Tilman et al 2011, Smith 2013, Godfray and Garnett 2014, Flachsbarth et al 2015) and is one of the main tradeoffs embedded in the recently adopted Sustainable Development Goals (ICSU 2016). Managing nutrient loadings to achieve food security while conserving the water environment constitutes a major challenge in the sustainability debate.

In addition to socioeconomic development, climate change is an important additional driver of variations in agricultural nutrient loadings. The impacts of climate...
change on agricultural nutrient loadings are two-fold: Firstly, climate change influences biophysical processes underlying the production of nutrient loadings; kinetics governing transformation and transport of nutrient elements in land systems are sensitive to temperature and precipitation. Secondly, climate change affects crop yields. This effect, combined with food demand variations originating from socioeconomic development, will reshape the landscape of global agricultural production.

Developing strategies to prevent and mitigate adverse impacts of agricultural intensification and climate change on water environments requires insights on how agricultural nutrient loadings could develop in the future. This paper develops projections of agricultural nutrient loadings, or annual yields of total nitrogen and total phosphorus delivered from agricultural land to freshwater environment, under joint impacts of socioeconomic development and climate change. To this end, we first set up a process-based model and use spatially disaggregated and crop-specific input data to estimate annual export rates of total N and total P to the freshwater environment from the production of major crops and global pasture land in a base year. We also project agricultural nutrient loadings in 2050 by linking the loading model with a base year. We also project agricultural nutrient loadings in 2050 by linking the loading model with a global partial equilibrium model of the agricultural sector, the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Robinson et al 2015). Based on the modeling results, spatial patterns of changes in global agricultural nutrient loadings are examined and the main drivers of loading variations are discussed.

2. Data and methodology

2.1. Loading model and input data for base year loading estimation

The loading model developed for this study calculates global agricultural nitrogen and phosphorus loadings on a 0.5° latitude by 0.5° longitude grid. Its development relies on the use of codes from the land phase simulation module of the Soil and Water Assessment Tool (SWAT) model (Arnold et al 1998). SWAT is a physically based river basin model and provides an integrated framework to simulate land phase and in-stream hydrologic and water quality processes. In land phase simulation, SWAT tracks the movement of organic and mineral forms of nitrogen and phosphorus in soils and estimates their export rates from land to water through leaching and sedimentation processes (Williams et al 1984). A detailed description of these algorithms is available in Neitsch et al (2011). SWAT has been extensively applied to estimate nutrient flows under varying climate, land use and management conditions and to evaluate long-term impact of climate change and water and land management practices (Gassman et al 2007, Tuppad et al 2011, Krysanova and White 2015). While reported applications of the SWAT model concentrate to river basins whose sizes range from a few hundred square kilometers to hundreds of thousands of square kilometers, the simulation algorithms in SWAT are highly scalable. As a demonstration, the model has been successfully applied in a number of continental-scale studies (Schuol et al 2008, Xie et al 2012, Abbaspour et al 2015).

The main input data sets used for the set up of the loading model and to inform model simulation for loading estimation in the base year of 2000 are listed in table 1. The elevation, soil, climate data are obtained from the USGS HydroSHEDS database, the FAO/ UNESCO Soil Map of the World, and retrieved through NASA POWER (Prediction Of Worldwide Energy Resource) agroclimatology data portal, respectively. Estimates for global atmospheric N deposition rate are obtained from Dentener (2006).

The rest of the data sets shown in table 1 contain information on global agricultural production system required for the simulation. The fertilizer use data developed by Mueller et al (2012) provide crop-specific
Table 2. Elements of the six alternative scenarios assessed out to 2050.

|                          | CSIRO-optimistic | CSIRO-medium | CSIRO-pessimistic | MIROC-optimistic | MIROC-medium | MIROC-pessimistic |
|--------------------------|------------------|--------------|-------------------|------------------|--------------|-------------------|
| Population in 2050       | 8.1 billion      | 9.3 billion  | 10.6 billion      | 8.1 billion      | 9.3 billion  | 10.6 billion      |
| Annual average rate of   |                  |              |                   |                  |              |                   |
| GDP growth               | 3.6%             | 3.2%         | 1.9%              | 3.6%             | 3.2%         | 1.9%              |
| Crop production          |                  |              |                   |                  |              |                   |
| Cereals                  | +61%             | +66%         | +68%              | +56%             | +61%         | +63%              |
| Cotton                   | +66%             | +69%         | +68%              | +63%             | +66%         | +64%              |
| Soybean                  | +66%             | +66%         | +58%              | +56%             | +55%         | +48%              |
| Livestock products       |                  |              |                   |                  |              |                   |
| Meat                     | +98%             | +96%         | +85%              | +97%             | +95%         | +85%              |
| Milk                     | +113%            | +117%        | +105%             | +114%            | +116%        | +103%             |
| Egg                      | +58%             | +60%         | +60%              | +58%             | +60%         | +60%              |
| Cropland area            |                  |              |                   |                  |              |                   |
| Rainfed                  | +13%             | +16%         | +17%              | +18%             | +21%         | +21%              |
| Irrigated                | +13%             | +16%         | +17%              | +14%             | +16%         | +18%              |
| Fertilizer nutrient use  |                  |              |                   |                  |              |                   |
| efficiency               | +40%             | +20%         | No change         | +40%             | +20%         | No change         |

estimates of N and P fertilizer application rates, whose development is based on Ramankutty et al (2008) and Monfreda et al (2008) M3 global cropland and pasture land data. The M3 cropland data present a geographic distribution of harvested area of individual crops. Rainfed and irrigated area are further disaggregated using the rainfed-irrigated area ratios derived from the MIRCA2000 database (Portmann et al 2010), and irrigation is simulated using the auto-irrigation function provided SWAT model. Crop calendar data are obtained from the Center for Sustainability and the Global Environment at the University of Wisconsin-Madison (Sacks et al 2010). Due to lack of data, crop rotation is not simulated.

Livestock animal excreta is another main source of nutrient inputs on agricultural land. In the estimation of excreta nutrient input rates, we follow the approach of Liu et al (2010). The quantities of cattle, pigs, sheep, goat and poultry excreta produced in stables and on meadows are calculated using livestock N and P excretion rates (Sheldrick et al 2003, Huffman et al 2008, Sprague and Gronberg 2013), GLW (Gridded Livestock of the World) livestock density values (Robinson et al 2007) and estimated shares of excreta produced in stables (Bouwman et al 1997). The excreta produced in stables is recycled to crop and pasture land as manure with the nutrient content of manure adjusted for losses in excreta collection and storage (Bouwman et al 1997, Sheldrick et al 2003). Shares of manure recycled to cropland range from 50%–90% in developed countries with an average application share of 66% (Liu et al 2010) while in developing countries 90% of manure is assumed to be put on croplands (Smil 1999).

All the input data noted above are mapped to the 0.5° latitude-longitude grid through aggregation, disaggregation or averaging.

In the simulation, the model is run with climate data series from 1997–2009. The first three years, 1997–1999, are used as a warming-up period, and the nutrient loadings are reported as averages during remaining ten-year simulation period. Model parameter values are estimated from input data or set to their default values by following standard procedures of SWAT setup (Neitsch et al 2011). Due to there is a lack of in-situ measurements of agricultural loadings, no further calibration is conducted. Considering constraints in model capacity and computational costs of modeling, simulation of nutrient loading from crops are limited to seven key crops: maize, rice, wheat, sorghum, millet and cotton and soybean, which account for close to 60% of the anthropogenic nutrient input to crop production. In this study, we focus on evaluating future trend of agricultural nutrient change and assume that simulation results are representative of the loading change patterns of the entire agricultural production system.

2.2. IMPACT and agricultural expansion/ intensification scenarios
In the assessment of nutrient loadings for future years, we base the estimation on agricultural expansion scenarios generated by IMPACT (Robinson et al 2015). IMPACT is a partial-equilibrium multi-market model of the agricultural sector. It simulates national and global food markets and provides a long-term vision of food demand, production, trade and prices of major agricultural commodities across the globe (Rosegrant et al 2002, Ringler et al 2010, Flachsbarth et al 2015, Robinson et al 2015).

IMPACT projects food supply and demand based on alternative population, economic growth and climate change scenarios among others. For this study six scenarios based on a combination of three population and GDP growth rates and two climate change pathways are used (table 2).

The three socioeconomic pathways can be described as ‘medium’, ‘optimistic’ and ‘pessimistic’, respectively, and are defined by different population and GDP growth rates. In the ‘medium’ case, the
world’s population will reach 9.3 billion people by 2050 (UN medium variant, 2008 revision); the annual global GDP growth rate is about 3.2% (based on rates from the World Bank EACC study by Margulis et al. (2010) with updates for Sub-Saharan Africa and South Asian countries). The optimistic pathway combines a lower population growth (UN low variant, 2008 revision) with a higher GDP growth (highest of the four GDP growth rates from the Millennium Ecosystem Assessment), and the pessimistic projection is characterized by higher population growth (UN high variant, 2008 revision) and lower economic growth (lowest of the four GDP growth rates from the Millennium Ecosystem Assessment).

The two climate change pathways (figure 1) are selected from an ensemble of projections on future climate generated by four general circulation models: CNRM-CM3, CSIRO-Mk3.0, and MIROC 3.2 (medium resolution) and ECHam5, under three SRES (Special Report on Emissions Scenarios) scenarios: A1B, B1 and A2. The CSIRO A1B and MIROC A1B are used in this study. In the former case, an increase in global annual mean precipitation by 4.8 mmH2O is projected along with a rise in global annual mean daily maximum temperature by 1.4 °C and global annual mean daily minimum temperature by 1.6 °C by 2050. In the latter case of MIROC A1B the projected increase in global average annual precipitation is as high as 34 mmH2O and the projected global annual mean daily maximum temperature and annual mean daily minimum temperature are 2.8°C and 3.0°C, respectively. The two scenarios are considered as two extremes of the climate change projection ensemble of dryness/wetness and have been selected to use in previous global assessments of food security (Nelson et al. 2010).

IMPACT projects that by 2050 the demand and associated production of five cereal crops, cotton and soybean will increase by 56%–68%, 63%–69% and 48%–66%, respectively with variations due to differences in population and GDP growth and in climate change. Correspondingly, the global rainfed area and irrigated harvested areas of the seven crops are projected to increase by 13%–21% and 13%–18%, respectively. The projection of cropland area expansion is based on exogenous projected rates of yield improvement due to technological change with impacts from population growth and climate change being taken into account. Generally, faster population growth leads to more rapid expansion of crop production levels. Moreover, cropland area expansion levels are higher under the MIROC climate change scenario compared to the CSIRO model. For livestock, production increases are in the range of 85%–98% for meat, 105%–117% for milk and 58%–60% for eggs. Under both future climate projections, people tend to consume fewer livestock products under pessimistic socioeconomic assumptions than under medium and optimistic socioeconomic assumptions due to the relatively higher prices for livestock products. IMPACT currently does not project changes in pastureland in response to changes in livestock production. Therefore, pastureland areas are kept unchanged in the scenario analysis.

In IMPACT, the globe is divided into 115 geopolitical regions and 281 food production units (FPUs) (see figure S1 in the supplementary information for the delineation scheme). Projections of crop and livestock production and crop area expansion are simulated at the FPU level. For this analysis, gridded estimates of cropland areas and livestock numbers in base year are scaled up to match the values projected

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3 Representative Concentration Pathways (RCPs) were adopted as updated scenarios in IPCC Fifth Assessment Report (AR5) in 2014. However, complete IMPACT projections under RCP scenarios were not available. IMPACT simulation results under SRES scenarios were adopted in this study.
by IMPACT in 2050 at FPU-level by assuming invariant spatial variability within each FPU. Moreover, the climate time series data representing future climate are constructed using the delta method (Gleick 1986, Lettenmaier et al. 1999) using downscaled GCM data provided by Jones et al. (2009).

While IMPACT provides projections on crop yields in future years, it does not simulate plant nutrient-yield relationships explicitly. The fertilizer application rates used to inform SWAT simulations in scenario analysis for 2050 are calculated according to the projected crop yields and assumed changes in fertilizer nutrient use efficiency in crop production (NUE, expressed in kg crop yield per kg of nutrients in fertilizer applied). We envision a greener world when the socioeconomic development is faster. World nutrient use efficiency in crop production is assumed to improve by 40% and 20% under scenarios with optimistic and medium population and GDP growths, respectively. Due to lack of data for developing spatially explicit and crop- and fertilizer- specific estimates for NUE variations, these assumed percent NUE improvement rates are applied uniformly to both nitrogen and phosphorus fertilizers, all crops and all countries except for least developed countries (LDCS in United Nations 2013). No changes in NUE are assumed under pessimistic projections of socioeconomic growth. The total quantities of livestock excreta and the quantities of excreta recycled to cropland as manure are also recalculated according to projected livestock animal population size in 2050 by omitting the changes in livestock N and P excretion rates and the excreta recycling rates.

In terms of atmospheric nitrogen deposition, a set of projected rates of atmospheric nitrogen deposition in 2050 are also available from Dentener (2006). We omit the difference between elements in scenarios used by Dentener (2006) to project nitrogen deposition in 2050 and in scenarios used by the IMPACT model and use the projected values from Dentener’s study (2006) as a proxy of future atmospheric N deposition rates across all IMPACT future scenarios.

### 3. Results

Total estimated global N and P loadings in the base year and under various socioeconomic and climate change scenarios are summarized in table 3. The estimated global N loading in the base year is 46 million tons yr\(^{-1}\). This estimate is comparable to the estimates computed from land nutrient budget analysis by Bouwman et al. (2013) (57 million tons yr\(^{-1}\)) and Liu et al. (2010) (47 million tons yr\(^{-1}\)). Note that we include fewer crops in our simulation, and Liu et al. (2010) limited their analysis to cropland and did not report the nutrient export rate from pasture land.

The estimated global P loading in the base year in our study is 2.7 million tons yr\(^{-1}\). The estimated value for this variable reported in past studies elsewhere are highly variable (MacDonald et al. 2011). Our estimate is at the low end of the range, and is close to the estimate of Bouwman et al. (2013) (4 million tons yr\(^{-1}\)).

Intensities of N and P loadings on a half degree latitude-longitude grid, which are calculated by normalizing the loading per cell by land area per cell, are presented in figure 2. Notably, high calculated loading values are found in northern and eastern China, the Indo-Gangetic plains of South Asia, the Midwestern United States and the central eastern South America. All these regions are large agricultural production centers. As a matter of fact, Brazil, China, India and the United States account for more than half of estimated global N and P loadings in the base year due to the large size of agricultural sector and high agricultural input level in these countries.

Global N and P loadings will increase by 2050 under all socioeconomic and climate change scenarios. Under the medium-CSIRO scenario, global projected 2050 N loadings amount to 68 million tons. Levels are lower under the optimistic-CSIRO scenario (62 million tons) and higher under the pessimistic-CSIRO scenario (73 million tons). Projected N loadings are substantially larger under the MIROC climate change scenario. Under the MIROC climate change scenario, 2050 N loadings are projected at 68 million tons, 74 million tons and 81 million tons per year under the optimistic, medium and pessimistic socioeconomic growth pathways, respectively. Patterns of change are similar for projections of P loadings but with lower overall projected growth. Under three scenarios with future climate projected by the CSIRO model, global P loadings are projected to increase to 2.8–3 million tons by 2050 and with MIROC climate to 3.1–3.4 million tons.

Detailed country-level results are shown in table S1 and table S2 in the supplementary data available at stacks.iop.org/ERL/12/104008/mmedia. While country-level results suggest substantial variation in projected growth of agricultural N and P loadings, a look at regionally aggregated results helps develop additional insight into how loading variations are driven by socioeconomic factors and climate change. Figure 3 shows the N and P loading rates by country group (low-income developing, middle-income developing and developed countries; refer to table S1 and

### Table 3. Estimated nutrient loadings in the base year (2000) and in 2050.

|            | Base year | 2050     |
|------------|-----------|----------|
|            | Optimistic| Medium   |
| N          | 46        | 62       | 68       |
|            | Medium    | 68       | 74       |
|            | Pessimistic| 73       | 81       |
|            | Optimistic| 2.7      | 3.1      |
|            | Medium    | 2.9      | 3.3      |
|            | Pessimistic| 3.0     | 3.4      |
In percentage terms, growth is fastest in the group of low-income developing countries with a projected increase by up to 118% for N loading and up to 47% for P loading. In contrast, growth is lowest in the group of developed countries except for P loadings under the CSIRO future climate, where P loading growth in the group of developed countries surpasses growth in the middle-income group of developing countries. Projected growth of N loadings range from 5%–49% for the group of developed countries and 33%–77% for the group of middle income countries. The ranges of projected P loading increase rates for the two group countries are 1%–49% for the group of developed countries and 1%–22% for the group of middle income countries. This varying growth is driven to a large extent by variations in population growth rates between these three groups (table 4) with most rapid population growth in the group of low-income countries driving food demand and agricultural production growth.

Projected nutrient loadings at the continent level are presented in figure 4. Projected growth rates by continent tend to be correlated with the pattern of precipitation change. Maps in the two upper panels of figure 1 present changes in annual precipitation levels projected by the CSIRO and the MIROC models, respectively. Although the MIROC scenario is regarded as a globally wet scenario and CSIRO is viewed as a globally dry scenario, projected precipitation changes are highly spatially heterogeneous. Under the MIROC scenario, precipitation is predicted to decline absolutely and in relation to the CSIRO model in the US, Mexico and much of Brazil, Argentina,
Peru, Chile and Venezuela, which cover the main agricultural production areas in North and South America. Corresponding with this change, rates of growth of nutrient loadings projected under MIROC are below those of the CSIRO scenario for these regions. This correlation is particularly visible for projected changes in P loadings. Erosion is the main mechanism for P loss from fields and the intensity of erosion is highly correlated with precipitation. Serving as another sign for the P loading-precipitation correlation, negative growths of P loadings relative to the loadings in the base year are projected under three CSIRO scenarios for Asia and Europe as well as the MIROC scenarios for North America. This corresponds with the projected future precipitation reduction under these climate change scenarios.

4. Discussion and conclusion

This paper presents a study to understand future trends of N and P loadings from global agriculture production systems. The results of the assessment validate growing concerns of large-scale additional pressures from agriculture on the water environment. Under all scenarios estimated global agricultural nutrient loadings will be substantially higher by 2050 relative to the base year. The scenario analysis results also reveal that both socioeconomic development and climate change will substantially affect agricultural nutrient loadings. Global nutrient loading variations caused by climate change are in the same order of magnitude as those found from scenarios across different population and GDP growth rates.

Although the level of nutrient water pollution also depends on dilution capacity of receiving water bodies which could be altered by climate change, the projected rapid increases in nutrient loadings without question sounds an alarm and calls for action to address agricultural pollution loadings to ensure that both food security and environmental sustainability goals under the SDGs can be met. The findings of this study highlight the needs to integrate management of
possible negative impacts of climate change on water quality into climate adaptation and mitigation plans. Furthermore, efforts need to strengthen particularly in the group of low-income developing countries because nutrient loads are projected to increase fastest there at the same time that resources to address growing pollution challenges are lowest in this group of countries rendering them more susceptible to the adverse impacts from water quality deterioration.

Like any other modeling work, our projections are inevitably subject to uncertainties and limitations. Key assumptions in the analysis are explained in previous sections. Among them, NUE change between 2000 and 2050 is undoubtedly one of the most critical ones, to which the results of scenario analysis are sensitive. As additional remarks, it should be noted in some countries NUE exhibited a decreasing trend in past few decades (Lassaletta et al 2014). These countries include China and India, two fast-growing economies and largest contributors of global agricultural nutrient loadings. The assumed NUE improvement in our study implies a reversal of such decreasing trend. The anticipation on occurrence of a reversal of the decreasing NUE trend can be largely justified by the environmental Kuznets curve (Yandle et al 2004), which states that at the initial stage of economic development environmental degradation tends to occur; but as economy continues to grow and after average income reaches certain level, environmental quality/performance improves with economic growth. Of course, it is highly uncertain when the turning point can be reached or if it can occur prior to 2050. Thus, there is even larger uncertainty arising from the NUE assumption in scenario analysis results for these

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**Figure 4.** Projected growth rates of N and P loadings by continent, 2000–2050.
countries. Secondly, it is also worth noting that many factors play in determining the nutrient use efficiency of crop production. Undue fertilizer subsidy policies and farmers’ lack of knowledge of fertilizer are two important reasons which lead to inefficient use of fertilizer. (Jia et al. 2013, Li et al. 2013). The assumed improvement in fertilizer nutrient use efficiency mainly reflects our expectation on better fertilizer policy and strengthened agricultural extension services in the future and are highly uncertain. Moreover, a range of agricultural technologies, such as land conservation, are available to reduce nutrient loadings from agricultural production. The effects of these technologies have been evaluated at a finer scale (e.g. Arabi et al. 2008, Ullrich and Volk 2009, Santhi et al. 2014), but are not incorporated in this global analysis due to the data constraints. This constitutes a limitation of our study but also implies opportunities to ameliorate the projected rapidly increasing trend of global agricultural nutrient loadings. The assessment of the relative contribution of alternative abatement technologies to addressing global growth in pollution is a topic for future research.

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