Turning points of global anthropogenic nitrogen creation and their climate effect

Baojing Gu[1,2,*], Xiaotang Ju[3], Yiyun Wu[2], Jan Willem Erisman[4,5], Albert Bleeker[6], Stefan Reis[7,8], Mark A. Sutton[7], Shu Kee Lam[9], Oene Oenema[10], Rognvald Smith[7], Deli Chen[9], Xinyue Ye[11]

[1]Department of Land Management, Zhejiang University, Hangzhou 310058, PR China
[2]Policy Simulation Laboratory, Zhejiang University, Hangzhou 310058, PR China
[3]College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, PR China
[4]Louis Bolk Institute, Hoofdstraat 24, 3972 LA Driebergen, The Netherlands
[5]VU Amsterdam, De Boelelaan 1091, 1081 HV Amsterdam, The Netherlands
[6]Netherlands Environmental Assessment Agency (PBL), Postbus 30314, The Netherlands
[7]NERC Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB, United Kingdom
[8]University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, United Kingdom
[9]Crop and Soil Science Section, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Victoria 3010 Australia
[10]Department of Soil Quality, Wageningen University, P.O. Box 47, 6700 AA, Wageningen, The Netherlands
[11]Department of Geography, Kent State University, Kent, OH 44242, USA

***Corresponding Author:**
Department of Land Management, Zhejiang University, Zijingang Campus, 866 Yuhangtang Road, Hangzhou 310058, PR China. Tel & Fax: +86 571 8898 2615. E-mail: bjgu@zju.edu.cn

Abstract
Reactive nitrogen (Nr) is both a limiting nutrient for food production and a major cause of global environmental and climate change. Managing Nr is crucial for its sustainable use in an increasingly affluent society (Zhang et al., 2015), especially as it may compromise the mitigation of global warming through interactions with the carbon cycle (Zaehle et al., 2011). The relation between Nr creation/release and carbon dioxide (CO_2) emission/sequestration with respect to economic growth remains uncertain. Here we report on the turning points of Nr creation and release, and CO_2 emission in relation to the growth of gross domestic product (GDP) per capita. Nr creation increases with GDP per capita until reaching a turning point, after which it tends to decrease with further economic growth. A similar pattern is noted for CO_2 emission and Nr release to the atmosphere. However, the ratio of CO_2 emission to Nr release to the atmosphere increases with economic growth without any turning point. This phenomenon suggests that the carbon sink in terrestrial ecosystems will be limited by Nr availability with economic growth in the future, and managing Nr for sustainable development may compromise the mitigation of global warming. Integrated management of carbon and Nr is therefore critical for future sustainable development and mitigation to climate warming.

Key Words
Economic development, turning point, CO_2 emission, climate change, nitrogen use efficiency, reactive nitrogen creation

Introduction

Anthropogenic reactive nitrogen (N_r, all N forms except N_2) inputs to terrestrial ecosystems through the Haber-Bosch process for N fixation (HBNF), biological N fixation via legume cultivation (CBNF) and unintended input via the emission and subsequent deposition of oxidized N (NO_x) emissions during fossil fuel combustion (NO_x-FF) have more than tripled the global annual rate of N input as compared to the pre-industrial era (Fowler et al., 2013). These inputs have exceeded the "safe operating space" for global societal development (Steffen et al., 2015).

Nitrogen plays a vital role in climate change through emissions such as nitrous oxide (N_2O)—the third largest contributor of greenhouse gas (GHG) to the global warming, and aerosols formed by N compounds (i.e. ammonium nitrates and sulfates) that alter the planet's reflectance (Erisman et al., 2011; Houlton et al., 2015). Human efforts in adapting to future climate change through increasing C sinks in terrestrial ecosystems are highly related N_r because of the C:N ratios are generally stable for the organisms and soil (Hungate et al., 2003; Tian et al., 2016). As a consequence, terrestrial N availability is vital to many aspects of the environment, society and climate systems (Erisman et al., 2011, 2013).

We analyzed global spatiotemporal changes in anthropogenic N_r creation and their environmental and climatic effects as a result of economic development using a panel data model for 132 countries from the years 1961 to 2008. The trends in N and C emissions to the atmosphere (including NO_x, NH_3, N_2O, CO_2, and total GHG) were also analyzed to quantify their environmental and climatic effects with economic development.

Methods

Data source. We compiled annual data for 1961–2008 on population and urbanization levels in 132 nations from the FAOSTAT database and GDP (expressed in real 1990 international dollars) from the Total Economy Database (GGD, 2008) on the cropland area, weighted yield of up to 275 crop types, and N and P fertilizer use from the FAOSTAT database.

Turning point in a country. A stepwise linear regression approach with one turning point was applied to N Fertilizer on GDP per capita series for each nation from 1961 to 2008.

$$y = \begin{cases} \beta_0 + \beta_1 x + \varepsilon, & x \le \alpha \\ \beta_0 + \beta_1 x + \beta_2 (x - \alpha) + \varepsilon, & x > \alpha \end{cases}$$

where x is GDP per capita; y is N Fertilizer; α is the turning point of GDP per capita; and β_0, β_1, and β_2 are regression coefficients; ε is the residual of the fit. The P-Fertilizer trend is β_1 before the turning point, and $\beta_1 + \beta_2$ after it. α is determined by least squares error methods. We also confined α to within the period 1965 to 2004 (1974 to 2004 for NO_x) to avoid a linear regression in one period having too few data points. To evaluate the necessity of introducing a turning point, a t-test was applied to test the null hypothesis that β_2 is not different from zero. Similar analyses have also been applied independently to NOx, and per capita NH_3 emissions. A probability level of $P<0.05$ was considered significant.

Panel data model. Considering the multiple interactions, we built a panel model to quantify the effect of GDP per capita on N input, and Nr and CO_2 emission. The panel model refers to compiling data on both the temporal and spatial scales simultaneously (48 years for 132 nations in this study, totalling 6336 samples, less than this value in the real analysis owing to data missing), also known as 'time-series cross-sectional data'. The panel model was constructed as follows in this study:

$$Y_{it} = c + PGDP_{it}\beta_1 + Dummy\beta_2 + \sum_j Ctrl_{itj}\,\beta_j + \mu_i + \varepsilon_{it}$$

where Y_{it} is the N input, and Nr and CO_2 emission in year *t* in country *i*; $PGDP_{it}$ is the annual GDP per capita; $Dummy$ is a binary parameter (0, 1) introduced to test whether the turning points of N_r fluxes and CO_2 emission exist with growth GDP per capita. All data of variables have been transformed logarithmically for the panel model analysis.

Results and discussion

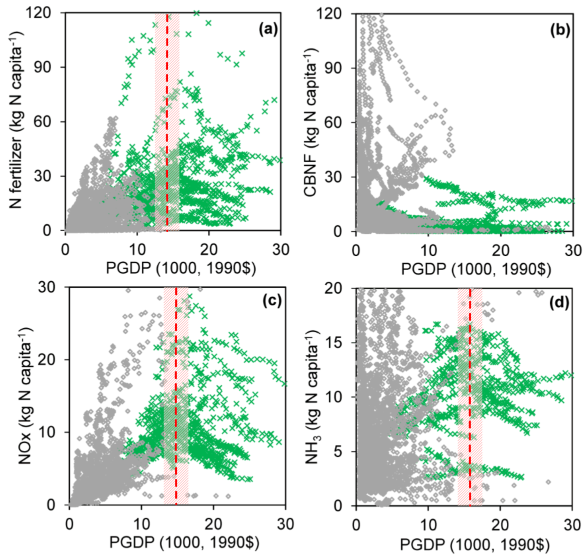
N_r creation and losses to the atmosphere

N fertilizer. A turning point was observed for N fertilizer application on the global scale by using dummy group testing (Table 1). The turning point was observed at a GDP per capita of around $14,000 (1990 international dollars by using purchasing power parity). A 1% increase in GDP per capita resulted in a 0.6% increase and 0.5% decrease in N fertilizer use before and after the turning point, respectively (Fig. 1).

CBNF. No turning points were observed for CBNF with the growth of GDP per capita (Table 1). Instead, per capita CBNF decreased exponentially with the increases in GDP per capita although the relationship varies widely among countries (Fig. 1). CBNF plays globally a supplementary role in food production compared to that of N fertilizer (Fowler et al., 2013).

NO_x. On the global scale, a turning point was also noted for per capita NO_x emissions from fossil fuel combustion regarding the growth of GDP per capita (Fig. 1). Economic growth has a larger effect on the reduction of NO_x emission after the turning points compared to that of N fertilizer use (Table 1). A 1% increase in the GDP per capita beyond the turning point results in a 1% reduction in per capita NO_x emission. Economic development significantly increases the energy use, but sharply reduces the NO_x emission per unit of energy consumed (NO_xE) after the GDP per capita reaches approximately $10,000.

NH_3. N fertilizer use is one of the major sources of NH_3 emission (Fowler et al., 2013). The growth of GDP per capita had no significant effect on NH_3 emissions despite N fertilizer use showing clear turning points with GDP growth on a global scale (Table 1, Fig. 1). Besides the emissions from N fertilizer, approximately half of the NH_3 emissions are derived from livestock production, with some variation on a national scale (Sutton et al., 2013).



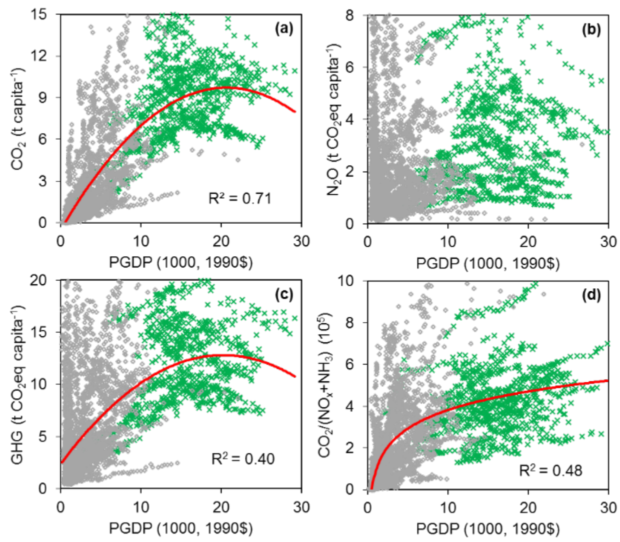


Fig. 1. Per capita Nr creation and release in relation to GDP per capita across 132 countries. (a) N fertilizer; (b) CBNF; (c) NOx emission from fossil fuel combustion; (d) NH3 emission. CBNF, cultivated biological N fixation. Dashed lines with red backgrounds represent the turning lines and their 95% confidence intervals with economic development. Green data points represent Type 1 countries with a turning point, and grey data points represent Type 2 countries without a turning point. There was no turning point for CBNF, and we applied the list of Type 1 countries of N fertilizer for CBNF due to the supplementary role of CBNF in food production compared to that of N fertilizer.

Fig. 2. Per capita greenhouse gas (GHG) emission in relation to GDP per capita across 132 countries. (a) CO2; (b) N2O; (c) Total GHG; (d) CO2/(NOx+NH3). Green data points represent Type 1 countries with a turning point, and grey data points represent Type 2 countries without a turning point. We applied the list of Type 1 countries of NOx for CO2/(NOx+NH3). R2 is the determining factor of regression curve. P<0.001 is for all the regression curves.

Table 1 Nonlinear effects of socioeconomic development on per capita N_r creation and loss, and their climatic effects by using the panel model

Variables	N Fertilizer	NO_x	CBNF	NH_3	CO_2	$CO_2/(NO_x+NH_3)$
Per capita GDP	**0.630*** (0.185)**	**0.309*** (0.064)**	**-0.733*** (0.013)**	0.043 (0.088)	**0.571*** (0.084)**	**0.468*** (0.090)**
Population	**0.875*** (0.225)**	0.126 (0.094)	**-0.031*** (0.012)**	-0.200 (0.115)	0.153 (0.147)	**0.477*** (0.130)**
Urbanization	-0.011 (0.009)	0.000 (0.004)	MC	0.011* (0.005)	-0.001 (0.005)	0.000 (0.005)
Group dummy	**2.547** (0.864)**	**3.472*** (0.399)**	NA	**0.043 (0.064)**	**1.460*** (0.342)**	NA
PGDP × dummy	**-1.002*** (0.307)**	**-1.295*** (0.136)**	NA	**-0.358 (0.184)**	**-0.571*** (0.125)**	NA
Intercept	-1.271*** (0.330)	0.291 (0.174)	3.222*** (0.030)	2.737*** (0.223)	0.394 (0.263)	3.395 (0.283)

N	5595	3842	4336	3347	3811	3347
R^2-within	0.223	0.550	0.457	0.264	0.540	0.280

Group dummy is a binary parameter (0, 1) introduced to test whether or not the turning points of N_r fluxes/CO_2 emissions exist with GDP per capita. For N Fertilizer, with GDP per capita <\$14,000 the group dummy is 0, while at GDP per capita ≥\$14,000 the group dummy is 1; for NO_x, NH_3, and CO_2, the critical per capita GDP is \$15,000 for the group dummy derived from Figure 1 and 2. We further tested the robustness of the group dummy using a range of per capita GDP (from \$10,000 to \$20,000 capita^{-1} yr^{-1} with \$1000 as interval) and found that the group dummy we set was the most significant. Cluster-robust standard errors (cluster at country level) were used for estimations. $^{***}P<0.001$, $^{**}P<0.01$, $^{*}P<0.05$; NA, not applicable; MC, multicollinearity with per capita GDP; R^2-within was estimated based on the group deviation method.

CO_2 and other GHG emissions

***CO_2*.** The majority of CO_2 emissions are produced by human activities, especially from fossil fuel combustion associated with economic development. We found that per capita CO_2 emissions (from fossil fuel use and cement production) significantly increase with the growth of GDP per capita on a global scale (Table 1). Energy consumption increases with GDP per capita, but levels off when GDP per capita reaches around \$20,000. CO_2 emissions per unit of energy supply (CO_2E) declines when GDP per capita is greater than \$10,000, which indicates that energy use efficiency increases with economic development. The changes in energy consumption and the CO_2E with the growth of GDP per capita result in a turning point of CO_2 emission at around \$15,000, which is very close to the turning points of N_r uses and losses (Fig. 2).

Integrated management of N and C

Although CO_2 emission and N_r release to the atmosphere (including NO_x and NH_3) respond differently to economic development, the ratio of $CO_2/(NO_x+NH_3)$ significantly increases with the growth of GDP per capita, without any turning point (Fig. 2). The majority of N_r emitted to the atmosphere will redeposit to the land surface (Fowler et al. 2013; Liu et al., 2013). This suggests that the relative N availability to the terrestrial ecosystems will be reduced relative to CO_2 emissions with economic development. N_r management will compromise the potential of C sequestration (Fig. 3).

Therefore, integrated management of N and C is essential for sustainable development on both the environment and climate in the future. Firstly, the development and adoption of clean energy or improvement in energy use efficiency via advanced technologies is crucial to the reduction of both CO_2 and N_r emissions to the atmosphere. Secondly, integrated management of C and N on landscape and regional scales. Integrated modelling of air pollution derived from Nr emissions and C emission/sequestration on regional scale will benefit the challenges on food security, environment and climate change.

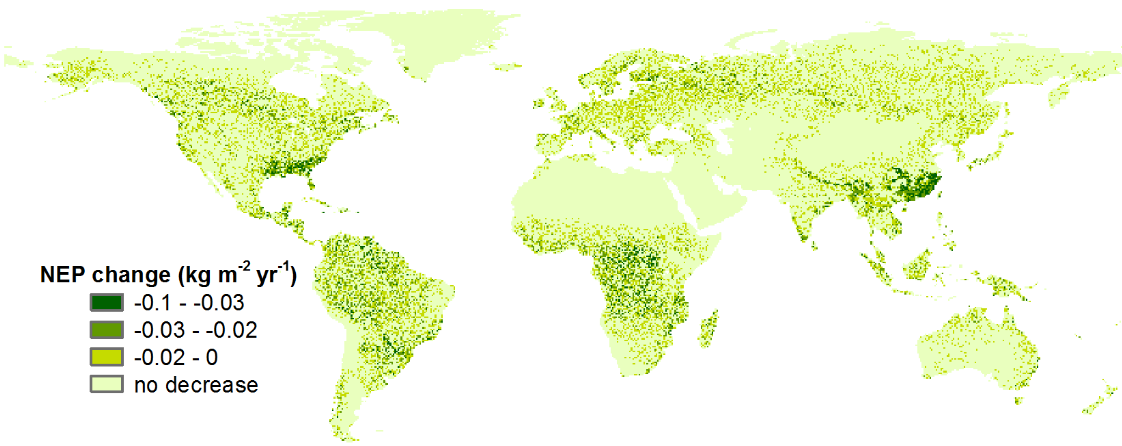


Fig. 3. Spatial variation of global net ecosystem productivity (NEP) considering N_r deposition changes with economic development in 2050. The storyline used in this simulation is the IPCC B1 scenario.

References

Erisman, J. W., Galloway, J., Seitzinger, S., Bleeker, A. & Butterbach-Bahl, K., Reactive nitrogen in the environment and its effect on climate change. *Curr. Opin. Env. Sust.* **3** 281 (2011).

Erisman, J. W. *et al.*, Consequences of human modification of the global nitrogen cycle. *Phil. Trans. R. Soc. B.* **368** 20130116 (2013).

Fowler, D. *et al.*, The global nitrogen cycle in the twenty-first century. *Phil. Trans. R. Soc. B.* **368** 20130164 (2013).

Houlton, B. Z., Marklein, A. R. & Bai, E., Representation of nitrogen in climate change forecasts. *Nat. Clim. Change* **5** 398 (2015).

Hungate, B. A., Dukes, J. S., Shaw, M. R., Luo, Y. & Field, C. B., Nitrogen and climate change. *Science* **302** 1512 (2003).

Liu, X. *et al.*, Enhanced nitrogen deposition over China. *Nature* **494** 459 (2013).

Sutton, M. A. *et al.*, Towards a climate-dependent paradigm of ammonia emission and deposition. *Phil. Trans. R. Soc. B.* **368** 20130166 (2013).

Steffen, W. *et al.*, Planetary boundaries: Guiding human development on a changing planet. *Science* **347** 1259855 (2015).

Tian, H. *et al.*, The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature* **531** 225 (2016).

Zaehle, S., Ciais, P., Friend, A. D. & Prieur, V., Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions. *Nat. Geosci.* **4** 601 (2011).

Zhang, X. *et al.*, Managing nitrogen for sustainable development. *Nature* **528** 51 (2015).