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Cleaning up nitrogen pollution may reduce future carbon sinks

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ABSTRACT

Biosphere carbon sinks are crucial for reducing atmospheric carbon dioxide (CO_2) concentration to mitigate global warming, but are substantially affected by the input of reactive nitrogen (N_r). Although the effects of anthropogenic CO_2 emission and nitrogen deposition (indicated by N_r emission to atmosphere) on carbon sink have been studied, it is unclear how their ratio (C/N) changes with economic development and how such change alters biosphere carbon sinks. Here, by compiling datasets for 132 countries we find that the C/N ratio continued to increase despite anthropogenic CO_2 and N_r emissions to atmosphere both showing an asymmetric para-curve with economic growth. The inflection points of CO_2 and N_r emissions are found at around $15,000 gross domestic product per capita worldwide. Economic growth promotes the use of N_r and energy, while at the same time increases their use efficiencies, together resulting in occurrences of inflection points of CO_2 and N_r emissions. N_r emissions increase slower but decrease faster than that of CO_2 emissions before and after the inflection point, respectively. It implies that there will be relatively more anthropogenic CO_2 emission but less N deposition with economic growth. This may limit biosphere carbon sink because of relative shortage of Nr. This finding should be integrated/included in global climate change modelling. Efforts, such as matching N deposition with carbon sequestration on regional scale, to manage CO_2 and N_r emissions comprehensively to maintain a balance are critical.

1. Introduction

Emission of carbon dioxide (CO_2) from human activities to the atmosphere is the most important driver of global warming, and the increase of atmospheric CO_2 concentration is responsible for ∼64% of the radiative forcing from well-mixed greenhouse gases (Thompson et al., 2016). Hence, stabilizing and ultimately reducing the atmospheric CO_2 concentrations is one of the principal mechanisms to mitigate anthropogenic climate change. Over half of current global anthropogenic CO_2 emissions are taken up by terrestrial ecosystems (30%) and oceans (25%), and the rest is accumulating in the atmosphere (Reay et al., 2008). Increasing CO_2 absorption in both terrestrial ecosystems and oceans is therefore a critical topic for the United Nations Framework Convention on Climate Change (UNFCCC) to reduce CO_2 accumulation in the atmosphere. External forces, such as human disturbances and climate change, could create a disequilibrium to alter

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global carbon (C) cycle (Luo and Weng, 2011). For instance, elevated CO_2 concentrations can increase the C sink of natural ecosystems in many Free-Air CO_2 Enrichment (FACE) experiments (Drake et al., 2011; Talhelm et al., 2014). However, these C sinks are often limited by the availability of nutrients such as nitrogen (N) and water (Hungate et al., 2003; Luo and Weng, 2011). Recent research showed that the rate of CO_2 uptake in Amazonian rainforests have decreased due to deficiency in nutrients such as N (Corlett, 2014). This suggests that the relative abundance of N input to ecosystems compared to atmospheric CO_2 concentration is crucial for the future increase in biosphere C sinks.

Economic drivers are crucial for determining future trends in CO_2 emissions and reactive N (N_r) use/loss (Chow and Li, 2014; Zhang et al., 2015; Li et al., 2016). For example, emissions of CO_2 and N oxides (NO_x) are closely related to fossil fuel combustion driven by economic development (Fig. S1). To meet human demand for food and energy, over 100 Tg N yr^{-1} (mainly ammonia (NH_3) and NO_x) have been emitted to the atmosphere in 2010, and about 70% of the N_r emitted is deposited on land surface, with the remainder deposited onto oceans (Fowler et al., 2013). This large amount of man-made CO_2 and N_r emissions substantially alters global C and N biogeochemical cycles through changing the C/N ratios (CO_2 to N_r emission) on multiple scales (Erisman et al., 2011, 2013). Elevated levels of N deposition have been found to increase C sinks in many terrestrial and oceanic ecosystems because of the removal of N shortage, as shown up in a reduced C/N ratio (Reay et al., 2008). Besides deposition, the input N can also be transferred to aquatic ecosystems through runoff from agriculture and human settlements, etc., which might increase the C sink in aquatic ecosystems (Erisman et al., 2011). However, these increased N_r fluxes have exceeded the "safe operating space" for global societal development, adversely affecting human health, ecosystems and the environment (Erisman et al., 2013; Steffen et al., 2015). N_r pollution is estimated to cost €70–320 billion per year in the European Union (Sutton et al., 2011), and $81–441 billion per year in the United States (Sobota et al., 2015). Activities that improve N use efficiency (NUE), i.e. to produce more food and energy with less N_r loss to the environment, have been proposed and implemented in many regions; these activities may increase the C/N ratio and affect C sinks in the biosphere (Chen et al., 2014; Lassaletta et al., 2014).

Environmental Kuznets Curves (EKC) have been widely applied to identify relationships between economic development and anthropogenic CO_2 emission, as well as N_r pollution, especially N_r loss from cropland (Chow and Li, 2014; Zhang et al., 2015; Li et al., 2016). However, little attention has been paid to changes in C and N stoichiometry of emissions to the atmosphere and its relevance for the global C sink, i.e., how climate change will be affected by changes in the C/N ratio of emissions under future economic development. Here, we analyzed global spatio-temporal changes in anthropogenic N_r inputs and losses, and CO_2 emissions as a result of economic development, using a panel data model for 132 countries from 1961 to 2008 (Fig. 1). Using these long-term data, we attempted to understand how C/N ratios change with economic development, predict their effect on terrestrial C sink capacity preliminarily and analyze the socioeconomic mechanisms behind the changes of the C/N ratio. In this paper, the C/N ratios refer to the ratios of anthropogenic emissions of CO_2 and N_r to atmosphere, including NH_3 and NO_x that is related to the N deposition to land surfaces. We put these in context with N_r losses and NUE in food and energy production, as well as related environmental issues.

2. Methods

2.1. Data sources

We compiled annual data on population and urbanization levels for 132 nations for the period of 1961–2008 from the FAOSTAT database (FAO, 2016) and GDP (gross domestic product, expressed in real 1990 international dollars, using purchasing power parity, PPP) from the Total Economy Database (GGDC, 2008). Data on cropland area, weighted yield of up to 275 crop types, and N and P fertilizer use were compiled from the FAOSTAT database. Per-capita fertilizer use and per-area fertilizer use were calculated as the annual N fertilizer use of a nation divided by the total population and cropland area, respectively. Cultivated biological N fixation (CBNF) was calculated for each nation based on the area of crop legumes, pasture and fodder legumes, and rice with N fixation rates of 115, 168 and 33 kg N ha^{-1} yr^{-1}, respectively (Herridge et al., 2008).

Per-capita fossil fuel energy consumption values and CO_2 emission from fossil fuel use combustion and cement production in the nations from 1961 to 2008 were obtained from the World Development Indicators dataset of the World Bank (http://databank.worldbank.org/). CO_2 emission per energy consumed (CO_2E) was calculated from CO_2 divided by the total fossil energy consumption of each nation. Total NO_x emissions from fossil fuel combustion and NH_3 emissions for the nations from 1970 to 2008 were collected from the Emission Database for Global Atmospheric Research (EDGAR, 2016). NO_x emission per energy consumed (NO_xE) was calculated from NO_x divided by the total fossil energy consumption of each nation.

2.2. Inflection point in a country

A piecewise linear regression approach, which has been widely used in many previous studies (e.g., (Piao et al., 2011)), was applied to CO_2 emission or Nr use/loss on per-capita GDP 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 per-capita GDP; y is CO_2 emission or Nr use/loss; α is the inflection point of per-capita GDP; and β_0, β_1, and β_2 are regression coefficients; ε is the residual of the fit. The CO_2 emission or Nr use/loss trend is β_1 before the inflection point, and $\beta_1 + \beta_2$ after it. All coefficients were determined by least-squares linear regression. We also confined α to within the period 1965–2004 (1974–2004 for NO_x) to avoid a linear regression in one period having too few data points. A probability level of $P < 0.05$ was considered significant. To check whether there could be more than one inflection point, we plotted the data from each country into a line chart to make sure that the inflection point detected is corrected.

2.3. Panel cointegration analysis

We applied recently developed panel unit root and panel cointegration techniques (Li et al., 2016) to estimate the cointegration relationships between economic growth and C/N ratios (emission of CO_2 to the emission of NH_3-N + NO_x-N) (Tables S1 & S2). We performed panel cointegration analysis as follows: *Step1*, we computed the summary panel unit root test on the levels of the series, along with a summary of the results, using individual fixed effects or both fixed effects and trends as regressors, and automatic lag difference term and bandwidth selection (using the Schwarz criterion for the lag differences, and the Newey-West method and the Bartlett kernel for the bandwidth). Most of the results indicated the presence of a unit root, since the Levin–Lin–Chu (LLC), Breitung, Im–Pesaran–Shin (IPS), and Augmented Dickey–Fuller–Fisher (ADF–Fisher) tests reject the null of a unit root. *Step2*, performing panel cointegration tests to determine whether per capita N_r use and loss, and their climatic effects had a cointegration relationship with socioeconomic development. We chose the deterministic trend specification according to the type of exogenous regressors and used the Schwarz criterion for the lag differences, and the Newey-West method and the Bartlett kernel for the bandwidth. Fisher/Johansen cointegration tests showed that the long-term cointegration relationship exists. *Step3*, Running the cointegration regression. After