Reactive nitrogen releases and greenhouse gas emissions during the staple food production in China and their mitigation potential

Longlong Xia[1], Xiaoyuan Yan [1*]

[1]Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China, llxia@issas.ac.cn, yanxy@issas.ac.cn

Abstract
Reactive N (Nr) releases are closely linked with greenhouse gas (GHG) emissions, and the simultaneous evaluation of them can help to develop overall effective mitigation options. In this study, we evaluated the characteristics of the Nr and GHG releases from staple food (rice, flour and corn-based fodder) production in China (2001-2010) and explored their mitigation potential. Results showed that there was a high spatial variation in the Nr and carbon footprints. Provincial Nr footprints had a significant linear relationship with carbon footprints, attributed to large contribution of N fertilizer use to both GHG and Nr releases. NH_3 volatilization and N leaching were the main contributors to the Nr footprints, while synthetic N fertilizer applications and CH_4 emissions dominated the GHG (carbon) footprints. About 10 (95% uncertainty range: 7.4–12.4) Tg Nr-N and 564 (404–701) Tg CO_2 eq GHG were released every year during 2001–2010 from staple food production in China. This caused the total damage costs of 325 (70–555) billion ¥, equivalent to nearly 1.44% of the Gross Domestic Product of China. A reduction of 92.7 Tg CO_2 eq yr^{-1} and 2.2 Tg Nr-N yr^{-1} could be achieved by reducing synthetic N inputs by 20%, increasing grain yields by 5% and implementing off-season application of straw and mid-season drainage practices for rice cultivation.

Key Words
Reactive nitrogen, greenhouse gas, food production, damage costs

Introduction
Staple food (rice, flour and corn-based fodder) production in China are projected to release substantial reactive N (Nr) and greenhouse gas (GHG), due to the excessive use of N fertilizer and other agricultural material (e.g., manure), and the lower current N use efficiency (Yan *et al.*, 2005; Chen *et al.*, 2014). Increases in Nr and GHG emission will cause a cascade of environmental problems, such as air pollution, stratospheric ozone depletion and eutrophication (Galloway *et al.*, 2008). There is increasing evidence that Nr release (Nr footprint) is closely interlinked with GHG emission (carbon footprint) (Cui *et al.*, 2013). For example, NH_3 volatilization, N_2O emission and N leaching, could be promoted linearly or exponentially, through N fertilization use, where N fertilizer production is an important contributor to carbon footprint (Zhang *et al.*, 2012). But few studies have evaluated both the Nr releases and GHG emissions through the perspective of life-cycle analysis in regional scales. This impairs the development of mitigation options for the simultaneous reduction of both Nr and GHG emissions. In this study, we did a preliminary evaluation of the Nr and carbon footprints of staple food production in China. We then assessed the total Nr and GHG releases, and their associated damage costs to environment and humans, as well as the mitigation potentials.

Methods
System boundaries
The system boundaries of the Nr and carbon footprints in our study were set as the period from the production of agricultural inputs to the distribution of the food to market. The food production and agricultural inputs data (between 2001 and 2010) come from the website of the National Bureau of Statistic of the People's Republic of China (http://www.stats.gov.cn/).

Nr and carbon footprint
The Nr footprint (g N kg^{-1} food) was calculated using the following equation:

$$\text{Nr footprint} = \left(\sum_{i=1}^{m} \mathrm{AI}_{i_{\mathrm{Nr}}} + \sum_{j=1}^{n} \mathrm{FC}_{j_{\mathrm{Nr}}} + \sum_{g=1}^{k} \mathrm{FP}_{g\ \mathrm{Nr}} \right) / \text{food yield}, \qquad (1)$$

where $\mathrm{AI}_{i_{\mathrm{Nr}}}$ denotes the Nr that is lost during the production and transportation of agricultural inputs (AI); $\mathrm{FC}_{j_{\mathrm{Nr}}}$ represents the Nr lost during farm cultivation(FC); and $\mathrm{FP}_{g\ \mathrm{Nr}}$ denotes the Nr discharged food processing (FP) and transportation.

The GHG footprint (g N kg^{-1} food) was calculated using the following equation:

$$\text{Carbon footprint} = \left(\sum_{i=1}^{m} AI_{i_{CO_2}} + \sum_{j=1}^{n} FC_{j_{CO_2}} + \sum_{g=1}^{k} FP_{g\ CO_2} \right) / \text{food yield}, \quad (2)$$

where $AI_{i_{CO_2}}$ represents the GHG emissions from AI. FC_{jCO2} represents the GHG emissions from FC. $FP_{g\ CO_2}$ denotes the GHG emissions resulting from FP sector.

The damage costs (¥) were assessed using following equation:

$$\text{Damage costs} = \sum_{i=1}^{n} (Nr_i A \times P_i) + CO_2 A \times P_{CO2}, \quad (3)$$

where $Nr_i A$ (kg N) denotes the amount of certain Nr (i) released; Pi (¥ kg^{-1} N) represents the cost of damage per kg of certain Nr (i) to the ecosystems and human health; and CO_2A (ton) and P_{CO2} (¥ ton^{-1}) represent the amount of GHG emissions and the damage costs per ton of CO_2 to the climate warming, respectively.

Mitigation scenarios

The 'business as usual scenario' (SBAU) was set first; that is, a scenario where no mitigation options were applied. The SBAU provided estimates of current carbon and Nr footprints. Many studies indicate that too much N is applied to croplands in China (Ju *et al.*, 2009; Zhang *et al.*, 2012). Thus, in scenario 1 (S1), synthetic N fertilizer inputs were reduced by 20% for each crop, in each province, while the grain yields were kept consistent with those in SBAU. The carbon and Nr footprints could be achieved by improving the grain yields, due to the current low grain yields in China. In scenario 2 (S2), the effects of a 20% N application reduction and 5% yield increase (compared to SBAU) were assessed. Scenario 3 (S3), CH_4 emissions were assumed to be further reduced by the off-season application of straw and mid-season draining of paddy fields on a nationwide basis, on the basis of S2.

Results

The Nr footprints of flour and fodder were obviously larger than that of rice (Fig.1). NH_3 volatilization dominated the rice Nr footprint, while N leaching was the largest contributor to the Nr footprints of flour and fodder production. The carbon footprint of rice production was 2.1 and 3.1 times that of flour and fodder, respectively, largely attributable to higher CH_4 emissions from paddy field. Synthetic N fertilizer production and application was the largest contributor to the carbon footprint of flour and fodder production.

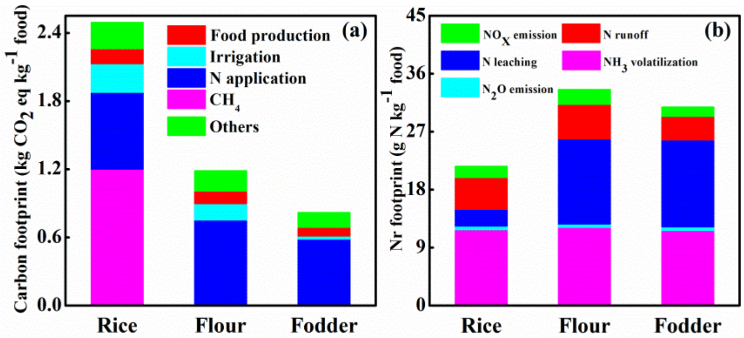

Fig.1. Contributions of different sources/activities to the (a) carbon footprints and (b) Nr footprints, of staple food production in China.

The Nr and carbon footprints were spatially heterogeneous across different provinces in China (Fig.2). Higher Nr footprints of food production mainly occurred in south China, within Yunnan, Sichuan and Hainan provinces. There were also large rice Nr footprints apparent in Beijing; large flour Nr footprints in Shanxi and Shaanxi provinces and large fodder Nr footprints in Shaanxi and Fujian provinces. These areas either had lower grain yields, or experienced larger N application rates than the national average level.

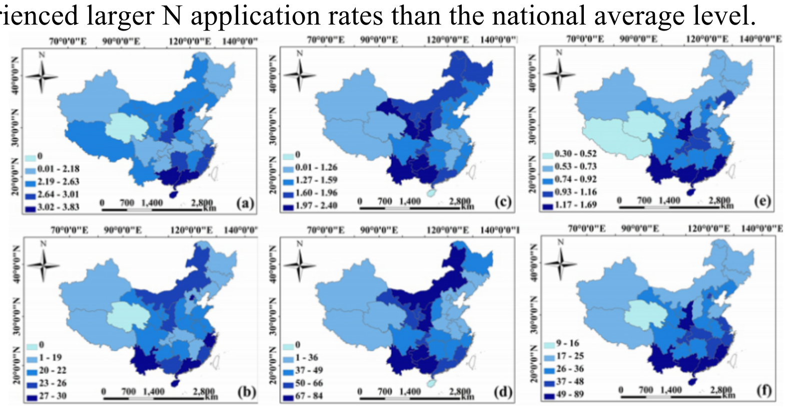

Fig.2. Spatial distributions of carbon and Nr footprints of staple food production in mainland China at the provincial scale. Carbon footprints (kg CO_2 eq kg^{-1} food): (a) rice; (c) flour; (e) corn-based fodder. Nr footprints (g N kg^{-1} food): (b) rice; (d) flour; (f) corn-based fodder. All plots have identical scale bar.

The Nr footprints for production of the three staple foods were found to highly correlate with the carbon footprints (Fig.3). Therefore, the provinces that produced higher Nr losses also had higher GHG emissions (Fig.2).

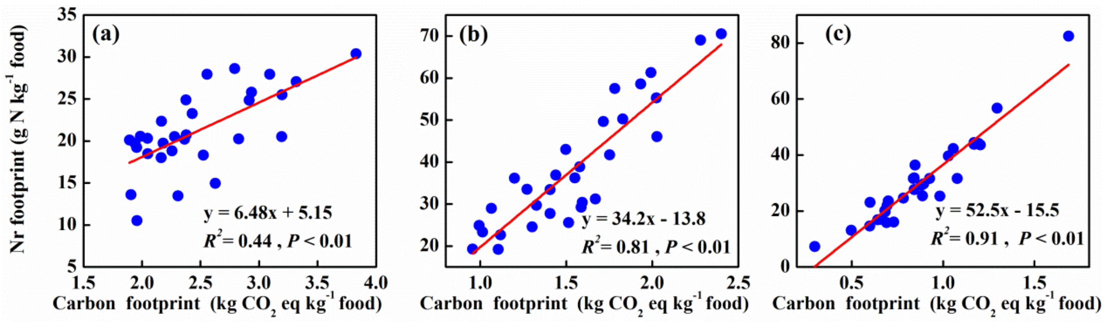

Fig.3. Spatial distributions of carbon and Nr footprints of staple food production in mainland China at the provincial scale. Carbon footprints (kg CO_2 eq kg^{-1} food): (a) rice; (c) flour; (e) corn-based fodder. Nr footprints (g N kg^{-1} food): (b) rice; (d) flour; (f) corn-based fodder. All plots have identical scale bar.

About 10 (95% uncertainty range: 7.4–12.4) Tg Nr-N yr^{-1} was evaluated to release into the environment during the production of these foods, with 2.8 (1.8–3.7), 3.1 (1.5–4.4) and 4.1 (2.8–5.7) Tg Nr-N yr^{-1} released during rice, flour and fodder production, respectively (Table 1). About 564 Tg CO_2 eq GHG yr^{-1} (404–701 Tg CO_2 eq) was emitted during the entire life-cycle of producing all three staple foods; with rice, flour and fodder contributing 333 (230–440), 114 (57–148) and 117 (65–164) Tg CO_2 eq yr^{-1}, respectively.

Table 1. Carbon and Nr footprints, and yearly GHG and Nr releases from food (rice, flour and fodder) production under different scenarios in China (2001-2010)

Food	SBAU[a]	S1[b]	S2[c]	S3[d]	SBAU	S1	S2	S3
	Carbon footprint (kg CO_2 eq kg^{-1} food)				Nr footprint (g N kg^{-1} food)			
Rice	2.49	2.30	2.20	1.84	21.6	17.9	16.8	16.8
Flour	1.18	1.03	1.00	---	33.5	26.6	25.0	---
Fodder	0.81	0.72	0.69	---	30.8	24.0	22.5	---
	Total GHG emissions (Tg CO_2 eq yr^{-1})				Total Nr releases (Tg Nr-N yr^{-1})			
Rice	332.9	310.1	311.4	264.9	2.77	2.31	2.28	2.28
Flour	113.8	99.7	101.0	---	3.12	2.43	2.39	---
Fodder	117.2	105.2	105.5	---	4.12	3.25	3.19	---

The total damage costs induced by the GHG and Nr releases were estimated to be 324.7 billion ¥ yr^{-1}, with a range of 69.5–555.2 billion ¥ (95% uncertainty), and of which rice contributed more than fodder and flour (Fig.4). The total damage costs accounted for nearly 1.4% of the average Gross Domestic Production in China between 2001 and 2010. The GHG emissions and NH_3 volatilization were the two largest contributors to the total damage costs.

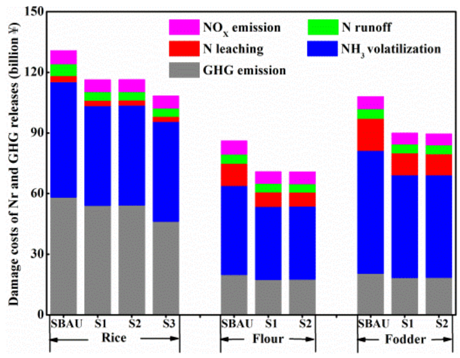

Fig. 4 Damage costs incurred by Nr releases and GHG emissions from staple food production under different scenarios in China.

Cutting the synthetic N inputs by 20% (S1) reduced the Nr (18-22%) and carbon footprints (8-11%), total Nr (7-12%) and GHG (17-22%) releases (Table 1), and the damage costs (11-18%) from staple food productions (Fig. 4). On the basis of N reduction, enhancing the yields by 5% further reduced the Nr and carbon footprints, but exerted insignificant effluence on the total Nr and GHG emissions. But the further reduction in the CH_4 in S3 could still reduce the damage costs (Fig. 4).

Discussion and Conclusion

Substantial Nr and GHG were released from staple food production in China, causing large damage costs to environment and human health. The dominant role of NH_3 volatilization and N leaching, N fertilization and CH_4 emissions in the Nr and carbon footprints suggested that high mitigation priority should be given to these items. The high spatial heterogeneity of Nr and carbon footprints was primarily a result of differences in the N fertilizer productivity efficiency; this highlights that mitigation options should be flexible and region-oriented (Zhang *et al.*, 2014). The significant linear relationship between the provincial Nr and carbon footprints of food production is attributed to the large contribution of N fertilizer to both Nr and GHG releases (Fig.4).This relationship demonstrated that a reduction in the use of N fertilizers could curb both GHG and Nr emissions. The scenario of reducing N rate (20%) and improving yields (5%) largely reduced the footprints and total Nr and GHG releases and the damage costs. To achieve this scenario, various knowledge-based managements should be adopted, such as split the N fertilizers into at least three applications for rice; applying two top-dressings for wheat and corn; as well as popularizing fertilizer deep placement for corn top-dressing (Zhang *et al.*, 2012; Chen *et al.*, 2014; Wang *et al.*, 2014). These N managements may add extra costs for farmers, which likely impedes the realization of above scenario (Wang *et al.*, 2014). A national ecological compensation scheme should therefore be established as an incentive for farmers to gradually adopt these knowledge-based management systems (Xia *et al.*, 2014).

References

Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X and Yang J (2014). Producing more grain with lower environmental costs. Nature 514, 486-489.

Cui Z, Yue S, Wang G, Meng Q, Wu L, Yang Z, Zhang Q, Li S, Zhang F and Chen X (2013). Closing the yield gap could reduce projected greenhouse gas emissions: a case study of maize production in China. Global Change Biology 19, 2467-2477.

Galloway J, Townsend A, Erisman J, Bekunda M, Cai Z, Freney J, Martinelli L, Seitzinger S and Sutton M (2008). Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320, 889-892.

Ju X, Xing G, Chen X, Zhang S, Zhang L, Liu X, Cui Z, Yin B, Christie P and Zhu Z (2009). Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proceedings of the National Academy of Sciences 106, 3041-3046.

Wang W, Koslowski F, Nayak D, Smith P, Saetnan E, Ju X, Guo L, Han G, Perthuis C, Lin E and Moran D (2014). Greenhouse gas mitigation in Chinese agriculture: Distinguishing technical and economic potentials. Global Environmental Change 26, 53-62.

Xia L, Wang S and Yan X (2014). Effects of long-term straw incorporation on the net global warming potential and the net economic benefit in a rice–wheat cropping system in China. Agriculture, Ecosystems & Environment 197, 118-127.

Yan X, Yagi K, Akiyama H and Akimoto H (2005). Statistical analysis of the major variables controlling methane emission from rice fields. Global Change Biology 11, 1131-1141.

Zhang F, Cui Z, Chen X, Ju X, Shen J, Chen Q, Liu X, Zhang W, Mi G and Fan M (2012). Integrated Nutrient Management for food security and environmental quality in China. Advances in agronomy 116, 1-40.

Zhang W, Yu Y, Li T, Sun W and Huang Y (2014). Net greenhouse gas balance in China's croplands over the last three decades and its mitigation potential. Environmental science & technology 48, 2589-2597.