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Greenhouse gas emissions and reactive nitrogen releases during the life-cycles of staple food production in China and their mitigation potential

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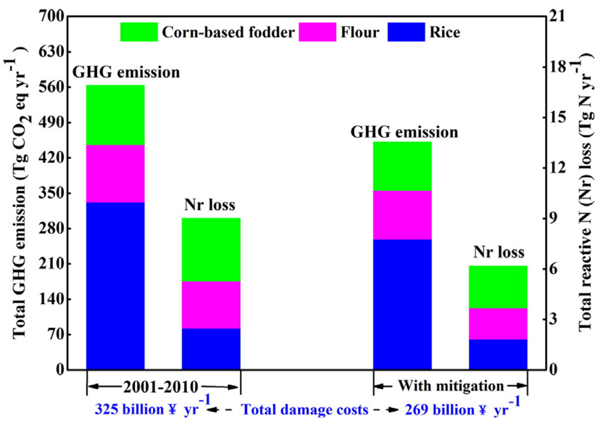
HIGHLIGHTS

- Carbon footprints of food production had a linear relationship with Nr footprints.
- 564 Tg CO_2 eq GHG and 10 Tg Nr-N were released from Chinese staple food production.
- The damage costs incurred by GHG and Nr releases reached 325 billion ¥.
- The GHG and Nr release possess large mitigation potentials.

GRAPHICAL ABSTRACT



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ABSTRACT

Life-cycle analysis of staple food (rice, flour and corn-based fodder) production and assessments of the associated greenhouse gas (GHG) and reactive nitrogen (Nr) releases, from environmental and economic perspectives, help to develop effective mitigation options. However, such evaluations have rarely been executed in China. We evaluated the GHG and Nr releases per kilogram of staple food production (carbon and Nr footprints) and per unit of net economic benefit ($CO_{2\text{-NEB}}$ and $Nr_{\text{-NEB}}$), and explored their mitigation potential. Carbon footprints of food production in China were obviously higher than those in some developed countries. There was a high spatial variation in the footprints, primarily attributable to differences in synthetic N use (or CH_4 emissions) per unit of food production. Provincial carbon footprints had a significant linear relationship with Nr footprints, attributed to large contribution of N fertilizer use to both GHG and Nr releases. Synthetic N fertilizer applications and CH_4 emissions dominated the carbon footprints, while NH_3 volatilization and N leaching were the main contributors to the Nr footprints. About 564 (95% uncertainty range: 404–701) Tg CO_2 eq GHG and 10 (7.4–12.4) Tg Nr-N were released every year during 2001–2010 from staple food production. This caused the total damage costs of 325 (70–555) billion ¥, equivalent to nearly 1.44% of the Gross Domestic Product of China. Moreover, the combined damage costs and economic input costs, accounted for 66%-80% of the gross economic benefit generated from

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food production. 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. In order to realize these scenarios, an ecological compensation scheme should be established to incentivize farmers to gradually adopt knowledge-based managements.

1. Introduction

Food production profoundly affects carbon (C) (Tilman et al., 2011) and nitrogen (N) cycles in ecosystems (Gu et al., 2012; Galloway et al., 2014). It was estimated that 819 Tg CO_2 equivalent (CO_2 eq; 1 Tg $= 1 \times 10^{12}$ g) was emitted in China in 2005 (representing 11% of the total national emissions) due to agricultural activities; within these activities, the production of staple grains (rice, wheat and corn) led to the majority of emissions (Cheng et al., 2014; Wang et al., 2014a). Moreover, about 27 Tg yr^{-1} of N fertilizer was applied for crop production during 2001–2010 in China (Yan et al., 2014), mainly to produce rice, wheat and corn (Huang and Tang, 2010). A significant proportion of the N fertilizer applied each year is released into the environment as reactive N (Nr; all N species except N_2), causing a cascade of environmental problems, such as air pollution, stratospheric ozone depletion and eutrophication (Galloway et al., 2008; Van Grinsven et al., 2013). The current high input and low use-efficiency of resources and energy, that occur during staple grain (or food) production, promote the deterioration of the climate and environment (Chen et al., 2014). To make matters worse, grain yields in China have suffered from stagnation in 79% of the national rice area, 56% of the wheat and 52% of the corn since 2000; but use of various related resources, such as pesticides and fertilizers, have likely continued to increase regardless (Ray et al., 2012; Shen et al., 2013). In other words, many Chinese farmers are likely purchasing (and using) an increasing amount of agricultural materials, but are receiving no obvious improvement in the net economic benefit (NEB) as a result (Zhang et al., 2012).

The above dilemma highlights the need for a comprehensive evaluation of current staple food production in China. Any such evaluation ought to incorporate both environmental and economic perspectives, in order to gradually achieve the goal of producing more food, with lower environmental costs and fewer economic and energy-related inputs (Xia and Yan, 2011; Chen et al., 2014). From the environmental perspective, assessing the greenhouse gas (GHG) emissions and Nr releases per unit of food (rice, flour and corn-based fodder) production (the carbon and Nr footprints), constitutes the primary focus (Leach et al., 2012; Cui et al., 2013a). From the economic perspective, efforts should preferentially focus on a cost–benefit analysis of the current staple food production; this should serve to clearly illustrate where the greatest damage costs occur during production, and which GHG or Nr species should be preferentially mitigated against (Van Grinsven et al., 2013).

Efforts have been made to evaluate parts of the carbon and Nr footprints of staple grain production, at the national scale, in China (Wang et al., 2014a; Yan et al., 2015). These studies focused on only one or two sectors (mainly the farm cultivation sector) and failed to address issues that are specifically related to the entire food production life-cycle. The life-cycle assessment (LCA) approach to food production starts with an assessment of the production of various agricultural materials and terminates when the food is distributed to markets or consumed by families; such assessments could help comprehensively evaluate the overall environmental consequences that are incurred at each step of the food production process (Leach et al., 2012). The 'authentic' hotspot sectors within the food production process, in terms of GHG emissions and Nr releases, could also be identified more accurately using the LCA approach. This, in turn, could facilitate formulation of effective sector-oriented strategies and mitigation options for specific types of food (Cui et al., 2013a).

Crucially, none of the aforementioned studies have simultaneously assessed both carbon and Nr footprints of staple food production. There is increasing evidence that the Nr footprint is closely interlinked with the carbon footprint (Erisman et al., 2011). For example, NH_3 volatilization, N_2O emission and N leaching, could be promoted linearly or exponentially, through N fertilization (Chen et al., 2014), and N fertilizer production is also an important contributor to carbon footprints (Zhang et al., 2013). Moreover, N fertilization has been reported to either enhance the activities of methanotrophs or promote inputs of root exudates, by stimulating crop growth (Banger et al., 2012), making it important in regulating CH_4 emissions (a hotspot sector of the carbon footprint for rice production) (Chen et al., 2014). However, the relationship between the carbon and Nr footprints, in terms of staple food production in China, remains unknown. This impairs the development of mitigation options for the simultaneous reduction of both carbon and Nr footprints.

Compared to only performing an environmental evaluation, combining such an evaluation with a cost–benefit analysis will likely help to translate what are sometimes highly specialized and technically scientific conclusions into information that is more accessible and meaningful to policymakers and citizens (Xia et al., 2014). This holistic approach for evaluating the carbon and Nr footprints of staple food production could assist farmers and consumers to understand the overall environmental and economic consequences of food production (Xia and Yan, 2012). Moreover, such cost–benefit analysis could provide guidance for emerging policy that aims to prioritize mitigation in hotspot sectors of carbon and Nr footprints (Van Grinsven et al., 2013). However, few economic and environmental analyses have been conducted in China that have considered both the carbon and Nr footprints of producing staple foods at the national scale. This lack of knowledge hinders the exploration of regional- or and crop-oriented mitigation options, and future improvements of farmers' incomes.

Therefore, the aims of the present study were to (1) quantify the average carbon and Nr footprints, the releases of GHG and Nr per unit of NEB ($CO_{2\text{-NEB}}$ and $Nr_{\text{-NEB}}$, respectively), the total GHG and Nr releases, and the aggregated damage costs of staple food (rice, flour and corn-based fodder) production in China, during 2001–2010; (2) analyze the characteristics of the carbon and Nr footprints, and the $CO_{2\text{-NEB}}$ and $Nr_{\text{-NEB}}$, and explore the societal and economic implications of these; and (3) explore the potential areas of mitigation of the carbon and Nr footprints, the $CO_{2\text{-NEB}}$ and $Nr_{\text{-NEB}}$ and the damage costs.

2. Materials and methods

2.1. System boundaries

The system boundaries of the carbon and Nr footprints (kg CO_2 eq kg^{-1} grain and g N kg^{-1} grain, respectively) for grain (rice, wheat and corn) production in our study were set as the period from the production of agricultural inputs to the harvesting of each crop grain. For food (rice, flour and corn-based fodder) production, two extra sectors were considered: the processing of each grain to food and the distribution of that food to market. Where we mention 'food' in this study, we actually mean 'food and feed' (i.e., including fodder, which is not a food item).