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Extension of residue retention increases net greenhouse gas mitigation in China's croplands

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ABSTRACT

Crop residue retention plays an important role in greenhouse gas (GHG) mitigation for global agriculture. To clarify the current status of residue retention and burning as well as the contribution of these processes to GHG dynamics, we conducted a nationwide survey on residue management in China in 2011 and improved the Carbon Accounting and Net Mitigation of Straw return model with updated parameters. The results indicated that residue retention increased from 144 Mt yr^{-1} in 2001 to 295 Mt yr^{-1} in 2011, whereas burned residue reached 200 Mt yr^{-1} in China. Because of these increases in residue retention, the net mitigation related to residue retention increased from 5.3 Tg Ce in 2001 to 13.3 Tg Ce in 2011. Further extension would sequester 15.8 Tg C, which is equivalent to a reduction in emissions of 3.9 Tg Ce from residue burning and a mitigate potential of 3.1 Tg Ce from replacing 1.5 Mt of nitrogen fertilizer. However, the national net mitigation from residue retention would achieve only 45–64% of the total soil C sequestration. The spatial heterogeneity of cropping systems and residue management was determined to have different effects on GHG dynamics. The net mitigation would have a negative value in eight provinces because of incremental increases in methane emissions from rice paddies. Increases in residue retention in the remaining 23 provinces would result in a maximum mitigation potential of 10 Tg Ce yr^{-1} and offset the carbon dioxide emissions caused by fossil fuel burning by 0.5% from the national value in 2011. Therefore, residue retention has mitigated a substantial amount of GHGs, and extending this strategy has considerable mitigation potential for China's croplands. Our results indicate that the retention and burning of crop residues have an effect on the GHG dynamics in China and represent potential strategies for mitigating climate change via residue management.

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1. Introduction

Reducing greenhouse gas (GHG) emissions and enhancing GHG sinks for climate change mitigation represent global challenges (Lal, 2004a). Agricultural production directly contributes to soil organic carbon (SOC) losses and anthropogenic GHG emissions (Smith, 2012). The carbon (C) lost from China's croplands from 1850 to 2000 was estimated at 5.86 Pg C (Houghton, 2002). Furthermore, the uplands of China emitted 3.0 Pg Ce (100-yr time horizon) of nitrous oxide (N_2O), and rice paddies emitted 3.1 Pg Ce of methane (CH_4) between 1961 and 2005 (Tian et al., 2011). The considerable C loss and current GHG emissions indicate that proper cropland management in China has a significant GHG mitigation potential (Lal, 2004b) because such management, including residue retention, recommended fertilization schedules and no-till farming, can mitigate atmospheric GHG levels by reducing emissions and sequestering C in biomass and soil (Jin et al., 2014).

The management of crop residues affects the C and nitrogen (N) cycles on croplands (Liu et al., 2014). In China, residue burning has been widely adopted during harvesting for faster removal with lower associated costs (Shi et al., 2014). In 2001, residue burning in China emitted 2.1 Tg Ce yr^{-1} of CH_4 and 0.6 Tg Ce yr^{-1} of N_2O (Lu et al., 2010a). Residue retention not only mitigates GHG emissions but also improves soil C sinks (Petersen et al., 2013; Zhao et al., 2014). Furthermore, residue retention can act as a substitute for synthetic N fertilizers (Gentile et al., 2009), thereby mitigating GHG emissions from N fertilizer production. However, residue retention

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has also been found to increase CH_4 emissions from rice paddies (Cheng et al., 2014) as well as GHG emissions because of the additional fuel used for tilling and ploughing (Lu et al., 2010b). Therefore, all of these factors must be considered when estimating the net effects of residue retention on GHG emissions.

Several studies have focused on the GHG dynamics of residue retention in China. Using the Straw Return and Burning Model (SRBM) and provincial residue utilization information from 2001, the net mitigation potential (NMP) obtained by replacing residue burning with residue retention at the provincial scale was 6.3 Tg Ce yr^{-1} (2010a), whereas when all residue from nine crops (e.g., rice, wheat, corn, sorghum, potato, rapeseed, sunflower, cotton and sugarcane) cultivated across China's croplands was returned, the NMP was 9.3 Tg Ce yr^{-1} (2010b). Lun et al. (2016) estimated the combined effect of performing fertilizer substitution with manure, residue retention, and conservation tillage on C mitigation in rice, wheat and corn in 2008 and generated a mitigation target set for 2020 in China. However, in these studies, the scenario settings and parameters were based on the published literature rather than on first-hand information from systematic surveys, or they did not consider non-CO_2 GHG in the mitigation estimations.

China accounts for the third largest area of croplands in the world. The total residue product on China's cropland increased from 660 to 807 Mt yr^{-1} between 2000 and 2009 (Jiang et al., 2012), whereas the use of residue as fuel decreased following economic development (Yao et al., 2012). Furthermore, Chinese governmental policies have been implemented to encourage the comprehensive utilization of crop residues (MEP, 1999; MOA, 2007). We hypothesized that these factors would stimulate an increase in the implementation of residue retention, which would affect the GHG budget of residue retention and burning. Our objectives were to (1) clarify the current status of residue retention and burning; (2) analyze the dynamics of realized net mitigation (RNM) of residue retention over the past decade; and (3) estimate the NMP under a full extension of residue retention in place of residue burning on China's croplands in 2011. To achieve these objectives, we conducted a nationwide survey of farmers between 2012 and 2013. By addressing these objectives, we can clarify the contributions of residue retention to GHG mitigation on China's croplands.

2. Materials and methods

We considered nine crops in China for this study: rice, wheat, corn, sorghum, potato, rapeseed, sunflower, cotton and sugarcane. The nine crops represent the main cereal or economic crops in China. The residue from other crops is typically used as forage or fuel because of the higher nutrient content or caloric content. The harvested area of these crops accounted for 67% of the total harvested area in China in 2011 (NBS, 2012).

2.1. Study region

In this study, Chinese croplands were divided into four cropping regions according to the heterogeneity of climate, cropping system and cultivation (Lu et al., 2009): northeast, north, northwest and south (Fig. 1). The cropping systems mainly involved one single crop per year in northeastern and northwestern China, double-cropping systems in northern China, and double or even triple cropping in southern China.

2.2. Field survey

From 2012 to 2013, we conducted a field survey of farmers on cropland management practices implemented in 2011 in 31 Chinese provinces (Fig. 1). The survey process involved a pilot survey, interviewer training, a formal survey and data entry and cleaning. This survey process is described in detail in Zhang et al. (2016). The survey included questions on the crop species and the percentage of croplands with residue retention and burning. In addition, triangulation questions were included on crop yields, residue retention types, and farmer attitudes toward residue retention, which were designed to ensure the questionnaire validity. We evaluated 752 valid farmer questionnaires, which included 1126 questionnaires from different crop seasons. The invalid questionnaires were those without any residue management or a sum of the percentage of all residue management practices that was more than 100. In addition, we conducted a survey on equipment use and the resulting fossil fuel consumption during cropland management from specialized agricultural machinery. Additionally, we obtained 40 valid questionnaires on machinery practices in China.

2.3. Data sources

In this study, the harvested area, cropland area and yield of the nine studied crops in 2001 and 2011 were obtained from the Chinese Statistical Yearbook from 2002 (NBS, 2012) and 2012 (NBS, 2012), respectively. The percentage of cropland with residue retention (PR) and burned residue (PB) in 2001 was obtained from studies by Lu et al. (2009) and Cao et al. (2008), and those for 2011 were obtained from the field survey.

Multiple cropping systems are widespread on China's croplands. In single-cropping systems, the harvested area equals the cropland area, whereas in multiple cropping systems, the harvested area is double or triple the size of the cropland area. The study area focused on cropland area that cultivated the nine studied crops (A_i), and it was calculated using formula 1 (Lu et al., 2009):

$$A_i = TCA_i \cdot \left(\sum HA_{ij}\right) \Big/ THA_i \quad (1)$$

where TCA_i represents the total cropland area of all crops in province i; HA_{ij} represents the harvested area of crop j (rice, wheat, corn, sorghum, potato, rapeseed, sunflower, cotton and sugarcane) in province i; and THA_i represents the total harvested area of all crops in 2011 province i (NBS, 2012). All areas have a unit of 10^3 ha.

2.4. Estimation of the GHG dynamics of residue retention and burning

We improved the SRBM model (Lu et al., 2010b) with a C Accounting and Net Mitigation of Straw return (CANM-Straw) model to inventory the GHG budget from residue retention and burning (Fig. 2). Both the CANM-Straw and SRBM include three parts: input, process and output. With the input of PR and PB, the models incorporated the effects of residue treatments when estimating the total effective GHG emissions (TEGEs) and subsequently determined the RNM and NMP generated via extension of residue retention (Fig. 2).

2.4.1. Inputs

The PR and PB from five scenarios were required to estimate the RNM for 2001 and determine the RNM and NMP for 2011. These treatments included the following: actual scenarios from 2001 to 2011, hypothetical scenarios for full burning in 2001 and 2011, and a hypothetical scenario for full retention in 2011. The sum of the PR and PB in the actual situation equaled either the PB under a full burning scenario or the PR under a full retention scenario.

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