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Carbon budget and greenhouse gas balance during the initial years after rice paddy conversion to vegetable cultivation

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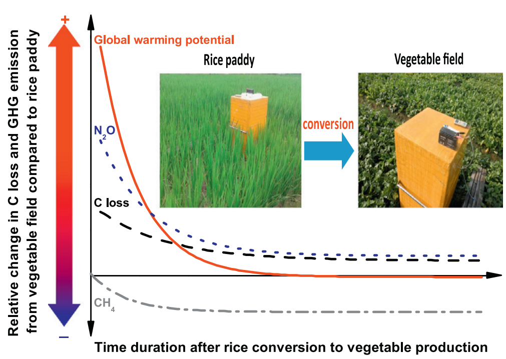
HIGHLIGHTS

- N fertilized rice paddy soil sequestrated 1.14 Mg C ha^{-1} yr^{-1}.
- Conversion of rice paddy to vegetable cultivation led to substantial soil C losses.
- Low C input and fast decomposition explained C loss after land-use conversion (LUC).
- The GWP (C loss, CH_4 and N_2O) strongly increased in the first year after LUC.
- It is especially critical to consider C and GHG balance in the first year after LUC.

GRAPHICAL ABSTRACT



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ABSTRACT

Rice paddy conversion to vegetable production is a common agricultural practice driven by economic benefits and shifting diets. However, little is known on the initial effects of this land-use conversion on net ecosystem carbon budget (NECB) and greenhouse gas (GHG) balance. Annual NECB and emissions of CH_4 and N_2O were measured from a native double rice cropping system (Rice) and a vegetable field recently converted from rice paddy (Veg) under no nitrogen (N) fertilization (Rice-N^0 and Veg-N^0) and conventional N fertilization (Rice-N^+ and Veg-N^+) during the initial four years upon conversion in subtropical China. Land-use conversion from rice to vegetable cultivation led to substantial C losses (2.6 to 4.5 Mg C ha^{-1} yr^{-1}), resulting from strongly reduced C input by 44–52% and increased soil organic matter mineralization by 46–59% relative to Rice. The magnitude of C losses from Veg was highest in the first year upon conversion, and showed a decreasing trend over time. N fertilization shifted rice paddy from a slight C source in Rice-N^0 (−1.0 Mg C ha^{-1} yr^{-1}) to a significant C sink in Rice-N^+ (1.1 Mg C ha^{-1} yr^{-1}) and alleviated the impact of land-use conversion on C loss via increased C input from higher crop productivity. Land-use conversion greatly increased the global warming potential (GWP) from Veg by 116–395% relative to Rice in the first year, primarily due to increased C losses and N_2O emission outweighing the decreased CH_4 emission. However, the GWP did not show obvious difference between Rice and Veg in the

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following years. N fertilization and land-use conversion interactively increased GWP in the first year via increased N_2O production. Concluding, NECB and GHG emissions in the first year after conversion are crucial and should be considered when evaluating the environmental consequences of land-use conversion.

1. Introduction

Rice is the staple food for over 50% of population on earth. As the world's largest rice producer, China contributed 35% of the world's total rice production in 2012 (FAO, 2013). Given the decline in profitability of traditional rice cultivation while increasing demands and economic benefits from vegetables, a considerable share of rice paddy fields have been and will still be drained for vegetable production in China (Hao et al., 2008; Lu et al., 2010). Previous studies demonstrated that agricultural land-use conversion (LUC) has consequences for soil physicochemical properties, biodiversity and the associated biogeochemical cycles (Kong et al., 2009; Sheng et al., 2013; Wang et al., 2014). Soil carbon (C) and nitrogen (N) cycling, and associated C balance and greenhouse gas (GHG) emissions are of increasing concern in the context of agricultural productivity and climate change (Lal et al., 2015; Weller et al., 2016; McCalmont et al., 2017).

Submerged conditions for rice cultivation have the potential to sequestrate C released by plants into the soil (Kögel-Knabner et al., 2010), and is responsible for considerable CH_4 emission (Linquist et al., 2012) while acting as negligible or relevant source and sink of N_2O (Meijide et al., 2017). Flooded rice paddy conversion to upland cultivation modifies cropping systems associated with differences in water regimes, cultivation intensification and N fertilization rates. These management practices have profound impacts on soil C and N transformation processes and therefore soil organic carbon (SOC) and GHG balance (Nishimura et al., 2008; Wang et al., 2014; Qin et al., 2016). Soil C dynamics is the predominant determinant of soil fertility and quality, and is closely related to crop productivity and sustainability (Lal, 2004; Nishimura et al., 2008). LUC induces changes in C inputs into the soil through rhizodeposits, dead roots, crop straws and organic manure incorporation, and C outputs by emissions of CO_2 and CH_4 and by dissolved organic carbon (DOC) leaching, leading to a net build-up or depletion of SOC pool (Nishimura et al., 2008). The magnitude of C input and output and resulting change rates of SOC stock following LUC varies widely over time, and is most pronounced during the initial years and become stabilized after decades (West and Post, 2002; Kurganova et al., 2014; Hounkpatin et al., 2018). The existing studies mostly evaluated the impact of LUC on soil C stock by estimating the overall loss or gain of SOC at steady-state conditions, ignoring the temporal dynamics of SOC during the initial years upon conversion (Batllebayer et al., 2010). Soil C change can be directly calculated by determining SOC stock in croplands using soil core sampling technique (Shang et al., 2011). However, significant changes in SOC in response to LUC cannot be detected in a short-term timescale, due to high spatial heterogeneity and huge background of SOC stock (Don et al., 2007; Smith et al., 2010). The net ecosystem carbon budget (NECB) analysis is a superior tool for indirectly determining the short-term C gains/losses relative to SOC stock variation (Smith et al., 2010). The NECB is the balance between C inputs and outputs. These C fluxes (C inputs and outputs) can be well quantified at finer spatial-temporal scale, thereby providing a scientific basis for improved understanding of C fluxes between the soil and atmosphere in response to LUC (Mu et al., 2008). CO_2 efflux derived from soil organic matter (SOM) mineralization is the primary pathway for C losses from soil and is a major component of terrestrial C budget (Fang et al., 1998; Nishimura et al., 2015). Large amounts of organic matter previously stored in paddy field are particularly vulnerable to increased decomposition after conversion to upland cultivation, potentially contributing to significant C losses (Nishimura et al., 2008). Studies on NECB in response to LUC are therefore required with respect to mitigating CO_2 emissions and helping maintain soil fertility for sustainable crop production.

Conversion of flooded rice paddy to upland vegetable cultivation reduces CH_4 emission via decreased production accompanying with increased CH_4 consumption (Liu et al., 2015, 2017). While this LUC enhances N_2O fluxes via accelerated N mineralization and increased mineral N supply for nitrification and denitrification (L. Wu et al., 2017). The mitigation benefits of CH_4 emission may be partially offset or even fully counteracted by the accompanying increased CO_2 and N_2O emissions in response to LUC. The balance among net emissions of CO_2, CH_4 and N_2O constitutes the overall global warming potential (GWP) of a cropping system. Thus, the trade-offs among changes in emission of these GHGs should be taken into account when assessing LUC response. However, most previous investigations on the impacts of LUC focused on SOC dynamics (Nishimura et al., 2008; Huang et al., 2014) and emissions of CH_4 (Eusufzai et al., 2010; Hu et al., 2016) and N_2O (Nishimura et al., 2005; L. Wu et al., 2017) separately and extensively. Comprehensive studies that simultaneously address NECB and the GWP in response to LUC are lacking (Weller et al., 2016). It also should be noted that the long-term effects of LUC on soil C balance and GHG emissions are quite different to the short-term impacts. Soil conditions immediately following LUC may accelerate C decomposition and nitrification coupled denitrification processes, possibly resulting in considerable changes in soil C balance and GHG emissions (Nikièma et al., 2012; Kraus et al., 2016). Significant knowledge gaps exist concerning soil C balance and the dynamics of GHG emissions in the initial years following LUC (Weller et al., 2016; X. Wu et al., 2017). Improved understanding the initial impacts of land-use conversion on NECB and GHG emissions is an urgent need to mitigate climate warming by maintaining crop productivity.

Nitrogen fertilizer application strongly influences the NECB in agroecosystems by promoting plant biomass production thereby increasing biomass returns (Pan et al., 2004), and by decreasing (Zang et al., 2016; Li et al., 2017) or increasing (Dossou-Yovo et al., 2016) the decomposition rates of organic residues and SOC. N fertilization can also regulate CH_4 emission through impacts on the activities of methanogens and methanotrophs (Bodelier and Laanbroek, 2004; Liu et al., 2017), and enhance N_2O emission via increased available substrates for nitrification and denitrification (X. Zhang et al., 2016). However, how LUC and N fertilization interactively affect soil C dynamics and GHG emission remains unclear.

The objectives of this study were to 1) quantify NECB and the dynamics of CH_4 and N_2O emissions, and their contributions to the GWP during the initial years upon rice conversion to vegetable cultivation, and 2) investigate how N fertilization modifies the effects of LUC on NECB and GHG emissions. We hypothesized that LUC from rice to vegetable cultivation will lead to substantial C losses, and increase the GWP. N fertilization will alleviate the effects of LUC on NECB, and enhance the effects of LUC on the GWP.

2. Materials and methods

2.1. Experimental field

The field experiment was conducted at the Changsha Research Station for Agricultural & Environmental Monitoring of the Chinese Academy of Sciences (28°32′46″ N, 113°19′50″ E, and 80 m elevation) in Jinjing town, Hunan Province, China. The study region belongs to a subtropical humid monsoon climate with annual mean air temperature of