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How well can we assess impacts of agricultural land management changes on the total greenhouse gas balance (CO_2, CH_4 and N_2O) of tropical rice-cropping systems with a biogeochemical model?

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ABSTRACT

Paddy rice is the main cropping system in Southeast Asia. However, water scarcity arising from competition from other sectors, rainfall variability and climate change increasingly challenges global rice production. One option to adapt to lower water availability is switching from paddy rice to less irrigation intensive upland cropping systems. Such land management change (LMC) is likely to significantly affect ecosystem carbon and nitrogen cycling and its greenhouse gas (GHG) balance. This study evaluates how well the ecosystem model LandscapeDNDC is able to simulate observed emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) from different tropical cropping rotations, i.e., double- and triple-cropped paddy rice, aerobic rice–paddy rice and maize–paddy rice (rice: *O. sativa*, maize: *Zea mays*) and how management changes to rice dominated lowland systems will affect the GHG balance on short (a few years) and long (several decades) time scales.

LandscapeDNDC predicts seasonal emissions of CH_4 and N_2O across different cropping rotations (including LMC) with R^2 values of 0.85 and 0.78 and average underestimations of 15 and 14%, respectively. In addition to emissions of CH_4 and N_2O, LandscapeDNDC also captures the long-term development of soil organic carbon (SOC). Soil oxygen status, growth of photosynthetic active aquatic biomass as well as decomposability of harvest residues significantly influence SOC development.

Simulation results demonstrate that short-term GHG balances after LMC considerably differ from long-term balances. Simulated total GHG emissions three years after LMC are highest for upland crop – paddy rice rotations due to pronounced decomposition of soil organic carbon. In contrast, the total GHG emissions are highest for double cropping of paddy rice and are clearly dominated by CH_4 emissions over a longer period of several decades. Simulation results suggest that approx. 2.8–3.4 t C ha^{-1} yr^{-1} residue incorporation after harvest is needed to achieve stable SOC stocks in mixed upland crop–paddy rice systems after LMC from double-cropped paddy rice systems.

1. Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contribute approximately 80% to the current global radiative forcing of well-mixed greenhouse gases (GHG) (Myhre et al., 2013). Among the most important anthropogenic emission sources of these GHG are emissions from land use and land management change (Ciais et al., 2013). Whereas flooded rice represents a major source of atmospheric CH_4, effectively all cropping systems are major emitters of N_2O, mainly due to the use of synthetic fertilizer for increasing crop production. However, the actual amount of N_2O emission varies depending on fertilization intensity, cropping system and other factors. Global source estimates in the year 2005 for these two atmospheric gases are 25–30 Tg CH_4-C yr^{-1} and 1.7–4.4 Tg N_2O-N yr^{-1}, representing approx. 1.5 and 5% of total anthropogenic GHG emissions, respectively (Herzog, 2009). After

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fossil fuel combustion, land use change (LUC) is the second most important source of anthropogenic CO_2 emissions. LUC has led to the release of approx. 180 Pg CO_2-C to the atmosphere since 1750 (Ciais et al., 2013) and is responsible for approx. 12% of total anthropogenic GHG emissions (reference year 2005; Herzog, 2009). Although at present the transformation of (sub-) tropical forests into agricultural systems and the related loss of plant biomass as well as soil organic carbon (SOC) is responsible for the largest part of LUC related CO_2 emissions (Don et al., 2011; Ciais et al., 2013), land management changes (LMC) such as the conversion of lowland (e.g., rice paddy production systems) into upland (e.g., maize) agricultural systems may result in large additional loss of SOC (Witt et al., 2000).

Paddy rice provides stable food to 1/3 of the world population (Devendra and Thomas, 2002) and is the dominating cropping system in Southeast Asia. Increasing water scarcity, changes in diets and demands from other sectors, e.g., biofuel production, however, leads to a growing number of farmers diversifying paddy rice with upland crop cultivation (Timsina et al., 2010, 2011). This is likely to cause major changes in the emissions of GHG from such systems. Weller et al. (2015b) recently reported that the change from paddy rice cultivation to upland maize production leads to "pollution swapping" with average seasonal CH_4 emissions decreasing from 58 ± 21 kg CH_4-C ha^{-1} to close to zero, while N_2O emissions substantially increase from 0.6 ± 0.3 to 3.9 ± 0.8 kg N_2O-N ha^{-1} under conventional fertilizer practices. However, consequences of such land management changes on SOC stocks remain still unclear.

In recent decades, numerous studies have been published on CH_4 and N_2O emissions from tropical cropping systems (e.g., Babu et al., 2006; Linquist et al., 2012; Wassmann et al., 2004; Weller et al., 2015a,b). Likewise, many studies analyze SOC dynamics in tropical lowland systems (e.g., Olk et al., 1996; Pampolino et al., 2008) as well as mixed lowland – upland systems (e.g., Huang et al., 2012; Pan et al., 2003; Wu, 2011; Yadav et al., 1998). So far only few studies (Cheng et al., 2014; Li et al., 2005; Shang et al., 2011) simultaneously evaluate N_2O, CH_4 and SOC stock changes and their contributions to the total GHG balance of an agricultural system or distinguish between short-term and long-term effects (Frolking et al., 2004; Li et al., 2005). The latter point is of primary importance since impacts of SOC decomposition on the GHG flux balance, in contrast to emissions of CH_4 and N_2O, is limited in the long-term by the establishment of a new equilibrium. Depending on the C input and outflow of the system, this equilibrium will occur most likely at a lower level (Johnston et al., 2009). Based on emission data from a recent field experiment (Weller et al., 2015a, 2016) at the International Rice Research Institute (IRRI), Philippines, our study contrasts short-term (3 years) and long-term (>30 years) impacts of land management changes on the total GHG balances (CH_4, N_2O and CO_2) of paddy rice cropping systems with the biogeochemical model LandscapeDNDC (Haas et al., 2013; Kraus et al., 2015). While it was shown that the $MeTr^x$ (Metabolism and Transport of compound x) biogeochemical submodel of LandscapeDNDC is able to simulate CH_4 and N_2O emissions from tropical lowland and upland systems (Kraus et al., 2015), the predictability of SOC dynamics on longer time scales has so far not been evaluated. Therefore, we tested the model on available datasets of long-term SOC changes of tropical rice-based cropping systems before applying it for simulating scenarios.

2. Material and methods

2.1. Field experiments

In this study, we examine three different field experiments that are conducted at the Experimental Station of the International Rice Research Institute (IRRI), Los Baños, Philippines (14°09′45″ N, 121°15′35″ E, 21 m a.s.l.), i.e., the long-term continuous cropping experiment (LTCCE), the long-term fertility experiment (LTFE) and the ICON experiment (Introducing Non-Flooded Crops in Rice-Dominated Landscapes: Impacts on Carbon, Nitrogen and Water Cycles). The Investigated crop rotations include paddy rice (*O. sativa*) and maize (*Z. mays*). While the LTCCE and the LTFE experiment have been started in the 1960s, the ICON experiment has been initiated only recently in 2012.

2.1.1. LTCCE experiment

The long-term continuous cropping experiment (LTCCE) at IRRI investigates the sustainability of intensive triple-cropped paddy rice cultivation under four different urea fertilizer regimes, i.e., no fertilizer, 120, 240 and 360 kg N ha^{-1} yr^{-1} (LTCCE0, LTCCE120, LTCCE240, LTCCE360) (Pampolino et al., 2008). The experiment started in 1963 with originally two rice crops per year and was intensified to three rice crops per year from 1966 onwards (one crop in the dry season [DS] and two crops in the early and late wet season [WS]). In the years 1991, 1993 and 1994 only two rice crops were cultivated with either dry or wet fallow periods in between growing seasons (Dobermann et al., 2000). Aboveground crop residues are completely removed after harvest (no stubbles left on the field). After soil puddling the soil is kept at saturated hydraulic conditions (no standing water) until 14 days after transplanting. Subsequently a water table of 0.05–0.1 m is maintained until harvest.

2.1.2. LTFE experiment

The long-term fertility experiment (LTFE) at IRRI compares the effect of different fertilizer regimes on yields for double-cropped paddy rice systems. The fertilizer regimes differ with respect to the amount of added nitrogen, phosphorus and potassium. Since LandscapeDNDC does not consider the latter two, only the amount of nitrogen is accounted for, which varies in the experiments between 0 and 250 kg N ha^{-1} yr^{-1} (LTFE0, LTFE250). After harvest, approx. 60% of straw yield is incorporated into the soil.

2.1.3. ICON experiment

The ICON experiment aims to explore environmental consequences of the change in management from double-cropped paddy rice cultivation to paddy rice (WS) diversified with upland crops in the DS, a management practice that is increasingly applied across Southeast Asia (Häfele et al., 2013; Timsina et al., 2011). The experiment encompasses three different cropping rotations, i.e., paddy rice–paddy rice (R), aerobic rice–paddy rice (A) and maize–paddy rice (M) (paddy rice: Tubigan 18, aerobic rice: Sahod Ulan 1, maize: Pioneer hybrid 30T80). Prior to the start of the experiment in the DS 2012, all fields were cropped with paddy rice in the DS and WS for at least two decades. For all cropping rotations three different fertilizer regimes are applied, i.e., no fertilizer, conventional fertilizer and optimized site-specific fertilizer application (0–180 kg N ha^{-1} $season^{-1}$, see Weller et al., 2016). The experimental data so far covers five consecutive cropping seasons from the DS 2012 to the DS 2014.

2.2. Model description

LandscapeDNDC is a simulation framework (Grote et al., 2009; Haas et al., 2013), which allows combination of various submodels describing water, carbon and nitrogen cycling and exchange processes with the atmosphere and hydrosphere of forest (Dirnböck et al., 2016; Molina-Herrera et al., 2015), grassland (Wolf et al., 2012; Molina-Herrera et al., 2016) and cropland ecosystems (Chirinda et al., 2011; Kim et al., 2014, 2015; Molina-Herrera et al., 2016). Kraus et al. (2015) extended