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Soil organic carbon sequestration and mitigation potential in a rice cropland in Bangladesh – a modelling approach

K. Begum[a,*], M. Kuhnert[a], J. Yeluripati[b], S. Ogle[c], W. Parton[c], M.A. Kader[d,e], P. Smith[a]

[a] Institute of Biological & Environmental Science, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK
[b] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK
[c] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA
[d] Department of Soil Science, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh
[e] School of Agriculture and Food Technology, University of South Pacific, Fiji

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ABSTRACT

An increase in the storage of carbon (C) in soil by changing management practices can help to mitigate climate change and increase soil quality. The objective of this study was to evaluate the best management options for reducing greenhouse gas (GHG) emissions. An ecosystem model DayCent was tested for two rice *(Oryza sativa* L.*)* experimental sites in Bangladesh. The sites are under different management practices and we first tested the models ability to simulate SOC turnover, and then estimated the potential for SOC sequestration by comparing change in SOC for each management scenario with baseline management (current farmers' practices) including conventional tillage, 5% residue incorporation and nitrogen (N) fertilizer. Predicted yield was also compared at both sites to ensure that yield was not compromised by mitigation measures. A control treatment was tested at both sites. At site 1, two other treatments of mineral N fertilizer, and combination of farmyard manure (FYM) and N were tested in a double rice based crop rotation. At site 2, a treatment receiving cowdung (CD) application, and a combination of CD and N were tested in a wheat (*Triticum* aestivum L.)-rice based crop rotation. The DayCent model was able to simulate SOC increase from the double rice test sites under unfertilized conditions, considering additional N and C sources in the simulations. Assuming N fertilizer (180 kg N ha^{-1} yr^{-1}) application for site 1, and CD application (25 t ha^{-1} yr^{-1}) for site 2, respectively, as the baseline, four single, and one integrated, scenarios were implemented in the model to predict SOC and yield at both sites. Two additional scenarios with alternate wet and drying (AWD) as a single treatment, and as part of an integrated approach, were also tested for their mitigation potential at site 1. The highest simulated positive impact on SOC development (60% higher than that of the baseline) was observed at site 1 when FYM was used in place of mineral N fertilizer. As there is a yield penalty associated with the use of only FYM, integrated approaches might show more promise, such as inclusion of 15% residue return, reduced tillage, less mineral N fertilizer, FYM addition, with or without AWD. This approach increases SOC by up to 23% while keeping the yield stable (nearly 3.5 t ha^{-1}). The application of CD only as determined for baseline of site 2, gives a yield of about 1.8 t ha^{-1} yr^{-1}. In contrast nearly two times more yield was obtained under the scenario associated with integrated management which also increases SOC by 30% relative to the baseline at the second site. Net GHG emissions, including nitrous oxide and methane emissions were estimated using the Intergovernmental Panel on Climate Change (IPCC) tier 1 methods, and country specific emission factors (where available), suggests that the integrated management scenario can reduce the net GHG emissions from 0.58-0.82 t carbon dioxide (CO_2)-eq. ha^{-1} yr^{-1} (equivalent to 0.16-0.24 t Ceq. ha^{-1} yr^{-1}) at site 2, while a net reduction in GHGs of nearly 1.00 t CO_2-eq. ha^{-1} yr^{-1} (equivalent to 0.27 t Ceq. ha^{-1} yr^{-1}) at site 1 was only achieved if AWD was also implemented with the integrated management scenario. Future studies could attempt to model non-CO_2 GHGs with a dynamic model.

* Corresponding author.
E-mail addresses: b.khadiza24@gmail.com (K. Begum), matthias.kuhnert@abdn.ac.uk (M. Kuhnert), Jagadeesh.Yeluripati@hutton.ac.uk (J. Yeluripati), stephen.ogle@colostate.edu (S. Ogle), billp@nrel.colostate.edu (W. Parton), mdabdul.kader@samoa.usp.ac.fj (M.A. Kader), pete.smith@abdn.ac.uk (P. Smith).

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1. Introduction

Agricultural land occupies approximately 70% of the 13 million hectare (Mha) of Bangladesh, and around 80% of this agricultural land is used for arable cropping (FAOSTAT, 2017). In 2014, around 34 million tonnes (Mt) of rice *(Oryza sativa* L.*)* was produced in Bangladesh, which is about 7% of global rice production (BBS, 2016). Agriculture is also estimated to be one of the largest sources of greenhouse gas (GHG) emissions in Bangladesh, estimated at 75 Teragram (Tg) carbon dioxide (CO_2)-eq. in 2014, and has increased by 55% over the period 1980–2014 (FAOSTAT, 2017). Although GHG emissions from agriculture in Bangladesh account for only ~1.4% of total global emissions (FAOSTAT, 2017), it is one of the most vulnerable countries in the world to climate change, due to its socio-economic conditions and geographical location (MOEF, 2008). Meeting the demands of an increasing population through sustainable agricultural practices is, therefore, a critical challenge for Bangladesh.

Researchers and policy makers in Bangladesh have focused mostly on adaptation to climate change rather than its mitigation. For instance in Bangladesh the Climate Change Strategy and Action Plan (BCCSAP) of 2009 had six pillars, with the fifth pillar providing only a brief outline about mitigation (Hussain and Rashid, 2016). In the Nationally Determined Contribution (NDC) 2015, Bangladesh pledged to reduce GHG emissions from non-agriculture sectors and emissions from agriculture were not included due to lack of available data (Hussain and Rashid, 2016). Nationally Appropriate Mitigation Actions (NAMAs), which are defined as any action that ultimately contributes to GHG reductions whilst addressing the development needs of the country, have been developed by the government of Bangladesh (GIZ, 2013). The goal is to reduce GHG emissions from baseline projections by at least one third by 2030 (Dion et al., 2012). Three NAMAs have been identified for agriculture: a) SOC sequestration in agricultural soils, b) improved rice cropping methods and c) improved water and energy-use efficiency.

It is estimated that close to 90% of the agricultural sector's total mitigation potential could be derived from SOC sequestration, with about 10% from reduction of non-CO_2 GHGs (Smith et al., 2007). Rice management offers substantial mitigation potential (Smith et al., 2008), which has been studied recently by researchers in Asia, including India (Nayak et al., 2012; Babu et al., 2006) and China (Wang et al., 2015; Nayak et al., 2015). Under modified rice management practices, SOC could be sequestered in India and China at a rate of about 8–16 Tg C yr^{-1} and 8–500 Tg C yr^{-1}, respectively (Lal, 2004; Xu et al., 2011). Compared to upland crops, paddy soils sequester more C due to long term reduction of microbial decomposition (Yan et al., 2013). Even in the unfertilized paddy rice fields in China, it was found that SOC increased by 13–60% in the control plot over a long term study (Yan et al., 2013; Hao et al., 2008; Tong et al., 2009). Yield also increased in unfertilized plots, and previous studies have suggest that external N sources like wet and dry deposition, microbial N fixation including photosynthetic bacteria, weeds, azolla, and blue green algae (BGA) growing in the standing water and soil water interface, contribute to N balances (Roger and Ladha, 1992; Mian et al., 1991; Pampolino et al., 2008). It is therefore necessary to further investigate the impact on SOC and yield of different management practices, including low nutrient inputs, as well as options to mitigate GHG emissions and maintain yield.

Although the mean technical mitigation potential for SOC storage under improved agricultural practices was estimated to be greater in South Asia than in either Africa or Europe (Smith et al., 2008), research on sequestration potential under different fertilization regimes in South Asian croplands, especially in Bangladesh, is scarce. In Bangladesh, two long term (over 20 years) fertilizer experiments have examined the effect of rice-based crop rotations on SOC (Karim et al., 1995; Egashira et al., 2003, 2005). However, there are still no estimates for the mitigation potential of the agricultural sector. The objective of the study, therefore, was to estimate the potential to increase soil organic carbon stocks and to evaluate the best management options for reducing GHG emissions. Several modelling studies (using e.g. DNDC, CENTURY) have simulated SOC change and mitigation potential with rice-based cropping systems in different regions of Asia (Xu et al., 2011; Bhattacharyya et al., 2007). For this study, we selected the DayCent model (Parton et al., 1998) because it can be readily be applied to croplands (Begum et al., 2017; Senapati et al., 2016), it has been tested in the global simulation of rice growth (Stehfest et al., 2007). This modified version has recently been applied for 350 rice based datasets in China (Cheng et al., 2014). The model was parameterised with a portion of the sites in China, and independently evaluated with other sites in that dataset. The results from China provide confidence that the model provides reasonable results for estimating SOC changes in paddy rice systems. GHG mitigation potentials were also determined in Chinese rice cropland using this model (Cheng et al., 2013, 2014). The DayCent model also tested in the United Nations for its applicability for use in GHG inventories (US EPA, 2017). Quantifying the potential for mitigation climate change through SOC sequestration while maintaining yield, will help policy makers to develop strategies to ensure environmental sustainability and to meet the challenge of feeding the growing population.

2. Materials and methods

2.1. Experimental sites

Data from two experimental sites in Bangladesh were used in this study. The sites belong to the Bangladesh Agricultural University (BAU) and Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), with their details summarised in Table 1.

The first long term field experiment is on a very young floodplain soil with a yearly irrigated rice-fallow-rainfed rice cropping rotation (Kader et al., 2017). Three crops were cultivated each year during 1978-1982. Rice was grown in two seasons: *aus* (March-June) and *aman* (July-November), with a pulse sown in the dry winter season (December-February). With the availability of irrigation facilities and high yielding varieties (HYV) rice was cultivated in two growing seasons from 1983 onwards.

Three sets of plots were simulated for site 1 (S1), including no application of fertilizer or manure (control), mineral nitrogen (N) fertilizer plots (MN), and combined application of N and farmyard manure plots (FYMN), which are common practices in Bangladesh. In the MN plot, the N rate varied (~70 kg N ha^{-1} yr^{-1}) depending on rice cultivars until 1982, but the rate was fixed at 180 kg N ha^{-1} yr^{-1} from 1982 onwards, when cultivation of HYV began. One-third of the N was applied just before transplanting of rice; the remaining portion was applied in two equal splits at 25–30 days and at 50–55 days after transplanting, respectively. In the FYMN plot, FYM (prepared with rice straw and cowdung, moisture content 60%, 1.1% N, with C:N ratio 27) application began in 1982, and was applied only before growth of the first irrigated rice. The N rate in the FYMN plot was half the N applied in the MN plot. The main source of water for *aman* season is rainfall which floods the soil, but irrigation water is supplied in case of insufficient rainfall, while irrigation by deep tube well is the main source of water during the *boro* season. To differentiate between the two rice seasons, irrigated rice or dry season rice is identified as R1, while rainfed rice or wet season rice is indicated by R2, respectively. Therefore, cropping seasons for S1 are indicated as S1R1 and S1R2, respectively.

The second experimental site (S2) is on a weathered terrace soil with a yearly wheat (*Triticum aestivum* L.)-fallow-rainfed rice cropping rotation. This site was established in 1988 to evaluate different manure management strategies with a control, cowdung (CD, prepared with only cowdung, moisture content around 72%, N content is 1.19% with C:N ratio 16) and a combination of CD and mineral N fertilizer (CDN), based on common management practices in the country. For wheat, half of the N fertilizer was applied during final land preparation and the rest was applied in two equal splits at 20–25 days and at 50–55 days