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# Impact of irrigation management on paddy soil N supply and depth distribution of abiotic drivers

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ABSTRACT

In rice production, water-saving irrigation management is expanding and likely alters depth profiles of soil moisture, redox potential (Eh) and microbial activity. It is, however, unclear how such conditions then impact net soil N-release and availability to the rice crop, because we do not know well enough how water-saving irrigation management shapes depth-distribution of Eh and reductive processes, and microbial activity. A field experiment with rice was laid out on a typical young floodplain paddy soil of Bangladesh with three irrigation schemes, viz. continuous flooding (CF), safe alternate wetting and drying (AWD) and direct seeded rice (DSR), with 120 kg N ha$^{-1}$ ($N_{120}$) or without ($N_0$) urea application. We evaluated changes in soil mineral N and plant N uptake, $CH_4$ and $CO_2$ emissions and soil pH, and at multiple depths soil Eh and temperature, dissolved C, Fe and Mn throughout 2015 dry (Boro) season (Jan–Apr). Eh stayed at or above ~ +300 mV except for sudden drops to ~ −200 mV with irrigation events in DSR. Eh quickly dropped to methanogenic conditions, under both AWD and CF; rises to ~ +200 mV were observed during AWD-drainage events but were restricted to upper 5.5 or 12.5 cm depths. Throughout the growing season there was a pronounced increase in reductive dissolution of Fe and Mn (hydro-) oxides, buildup of dissolved C, and $CH_4$ effluxes under AWD and CF but not DSR, likely at least partially driven by the gradual soil warming from ~20 °C till 28 °C. Predominant aerobic conditions under DSR lead to a nearly doubled C-emissions ($CO_2$ + $CH_4$) compared to AWD and CF, suggesting more soil organic matter (OM) degradation in the former case, while soil mineral N plus plant N build-up rate followed an opposite order. Urea application did not raise soil exchangeable N levels, even prior to significant plant uptake from 28 DAT (days after transplanting), and we forward temporal abiotic $NH_4^+$-fixation and N-removal processes as explanations. We conclude that regardless of some distinctions in temporal evolutions of puddle layer Eh, solution C, Fe and Mn, and $CH_4$-emission, soil N-supply was quite comparable under AWD and CF, as was rice yield. In the context of N availability, AWD could be safely adopted for rice growth in the Bangladeshi Boro season. The eventual fertilizer N recovery efficiency was higher for CF (42%) than for AWD (32%), but AWD saved 12% irrigation water. While DSR saved 45% water there was a large yield penalty, likely due to drought stress but also by poor germination caused by cold night temperatures in mid-January, while seedling transplantation in CF and AWD plots was only later on 28 January. Further research should be conducted to investigate the fast and pronounced removal of exchangeable inorganic N after initial N buildup by soil OM mineralization, especially in CF and AWD. At this moment most likely candidate processes appear clay-$NH_4^+$ fixation and anaerobic $NH_4^+$-oxidation.

## 1. Introduction

N fertilizer recovery is generally low for rice (*Oryza sativa*), approx. 31–40% (Cassman et al., 2002) compared to other cereals, and a substantial part (34 to 46%) of N taken up by rice plants derives from native soil supply. Hence organic matter (OM) mineralization (≥50%

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of rice's N demand) (Zhu, 1989) and possibly also $NH_4^+$-defixation are essential to meet the rice N demand. Understanding the patterns of soil mineral N and crop N uptake throughout rice growing season is crucial to develop appropriate N fertilizer advice. Whereas blanket N-doses are still usually applied, regardless of the considerable cost to many South-East Asian farmers. Besides N, water supply is another important factor sustaining rice production because cultivated rice is highly sensitive to water shortage and requires 2500L water $kg^{-1}$ grain production (Bouman, 2009). Out of 75 million hectares of irrigated rice area, in Asia, 15–20 are expected to experience water shortage by 2025 (Tuong and Bouman, 2003). Dry season irrigated (Boro) rice contributes more than half of the national rice production in Bangladesh. Underground water is pumped up to keep paddy fields flooded during various growth stages (Parvin and Rahman, 2009; Price et al., 2013). This dependency on ground water reserves draws down the water table and makes irrigation water a costly input for farmers, approximating 25–30% of the production cost. Therefore the promotion of water-saving irrigation managements, especially alternate wetting and drying (AWD) and direct seeded rice (DSR), in South-East Asia and now also in Bangladesh is growing steadily. Relative to CF, adoption of DSR and AWD might save up to 50–70% and ~35% water, mostly by maintaining soil moisture level at field capacity and flood water level at ≤ 15 cm from soil surface, respectively (Rahman and Masood, 2012; Price et al., 2013). Hence both techniques could enhance water productivity, minimize non-beneficial water flows (i.e. seepage, percolation and evaporation) (Bouman et al., 2005), and N leaching losses from paddy fields, according to Tan et al. (2015) by 3–24%.

Associated changes in alternation of aerobic and anaerobic conditions in paddy fields has, however, been reported to enhance gaseous N losses via nitrification-denitrification (Dong et al., 2012; Reddy and Patrick, 1975) and is expected to alter soil physicochemical properties like the use of oxidants for soil OM decomposition, level of dissolved OM, soil pH and Eh compared to continuously flooded, (CF) fields (Kögel-Knabner et al., 2010; Pan et al., 2014). Soil microbial activity and N supply processes are largely driven by these abiotic factors whose depth profiles are expected to differ strongly in continuously and non-continuously flooded fields. It is difficult to predict just how a rise in Eh and lowering of pH via re-aeration and concomitant decrease in methanogenesis (Minamikawa and Sakai, 2006; Moterle et al., 2013) and reduced species like $Fe^{2+}$ and $Mn^{2+}$ (Gotoh and Yamashita, 1966; Pan et al., 2014), will impact soil N-supply from non-continuously flooded paddy fields.

On the one hand it is generally assumed that net release under anaerobic conditions is higher due to lower metabolic N requirements of anaerobes under flooded (Kader et al., 2013; Ono, 1989; Patrick and Wyatt, 1964; Reddy and De Laune, 2008) than non-flooded or continuously aerated conditions. But flooding on the other hand could decline fertilizer derived and indigenous available N through enhanced immobilization (Cucu et al., 2014; Devêvre and Horwáth, 2000). Furthermore, in paddy soils facing short and frequent draining-rewetting events, SOM may decompose at a faster rate and $NO_3^-$ formed by nitrification may quickly lost by denitrification in subsequent wetting; together increasing C and N losses (Reddy and Patrick, 1975; Tan et al., 2015). Soil OM decomposition and consequent N mineralization in flooded paddy soils furthermore depends on the kind and amount of reducing and oxidizing agents, like $NO_3^-$, $Mn^{3+/4+}$, $Fe^{3+}$, $SO_4^{2-}$ and $CO_2$, with easily oxidizable substrates like dissolved OM and most abundant reducible agents like Fe- and Mn-(hydr-)oxides being most important (Li et al., 2010; Ponnamperuma, 1972). A link between N and Fe cycles was already suggested from our previous laboratory and greenhouse studies with Bangladeshi paddy soils (Akter et al., 2016; Akter et al., 2018), where we found positive correlations and a close temporal synergy between dissolved Fe and soil mineral N buildup. OM adsorbed by clay minerals and Fe- and Mn- (hydr-)oxides is released as dissolved OM under reducing conditions by reductive dissolution or desorption via a pH rise and may be readily available for microbial degradation and thereby contribute to mineral N release, or act as an intermediate transitional pool for subsequent mineralization (Grybos et al., 2009; Huang et al., 2016; Li et al., 2010; Said-Pullicino et al., 2016). Yet, net effects in the field could be complicated because Xu et al. (2013) for example, found that fluctuation in Eh due to multiple wet dry cycles increased dissolved OC content in the surface but decreased it in the deeper soil by diminishing leaching and percolation. Lastly, reduction of the $Fe^{3+}$ in clay minerals (e.g. vermiculite or interstratified vermiculite-chlorite) or dissolution of Fe-(hydr-)oxides coatings on clay surfaces at low Eh could also favor release of fixed $NH_4^+$, and hence influence soil exchangeable N levels (Brookshaw et al., 2016; Scherer and Zhang, 1999).

The majority of detailed studies on paddy soils' N mineralization have, however, been conducted in laboratories or green-houses (Narteh and Sahrawat, 2000; Akter et al., 2018) under continuous flooding or draining conditions using soils from surface layers. But then the ability to assess dynamics of depth profiles of physicochemical driving variables of N mineralization was limited. Therefore, a field experiment was conducted to test to what extent and depth, reductive dissolution of Fe and Mn, occurrence of anaerobic conditions and microbial activity differ between soils under continuous and water-saving irrigation alongside soil N supply. We expected that non-continuous flooding would lower soil N supply because 1° aerobic OM degradation results in less net N-release than anaerobic microbial activity (Reddy and DeLaune, 2008), 2° $NH_4^+$-defixation would be limited (Cucu et al., 2014) and 3° release of dissolved OM is reduced compared to under continuous flooding (Said-Pullicino et al., 2016). We compared urea-fertilized and unfertilized paddy fields in addition to compare urea fertilizer N-use efficiency in function of irrigation regime. We conducted a depth-differentiated follow up of the dynamics of pH, Eh, dissolved C, solution Fe and Mn *in-situ* under three irrigation managements (CF, AWD and DSR) in a young floodplain paddy soil in Bangladesh during the Boro rice growing season. Simultaneously we measured mineral N build-up in soil and plant, topsoil pH, and $CH_4$ and $CO_2$ emission as a measure of general soil biological activity.

## 2. Materials and methods

### *2.1. Site description, soil properties and materials*

The field experiment was conducted in 2015 on a paddy field managed by the Soil Science Dept. of Bangladesh Agricultural University (24°42′55″N, 90°25′47″E, average altitude 18 m). The selected soil and management were typical for the North of Bangladesh: Rice-Fallow-Rice cropping on a non-calcareous dark grey Floodplain soil, with a subtropical monsoon climate, annual mean temperature of 25.8 °C and rainfall of 2427 mm (BMD, 2015) mostly between April to October. We monitored soil biochemical properties, crop growth and N-uptake during dry Boro rice growing season (January to May), during which no or low rainfall necessitates flood irrigation of pumped-up ground water. Air temperature and rainfall data were obtained from the weather station 2 km away from field, at the university campus.

The plow layer and plow pan extended from 0 to 15 cm and 15–21 cm depth, with bulk density of 1.1 and 1.5 g $cm^{-3}$, respectively. Main physical and chemical soil properties of the surface (0–15 cm) and subsoil (15–25 cm) layers at initiation of the field trial are given in Table 1. The soil texture was silt loam with a neutral pH($H_2O$). Soil porosity, total C and N, ammonium oxalate extractable Fe and Mn, and exchangeable $NH_4^+$ contents were greater in the surface soil than in the subsoil. The levels of essential plant available nutrients in the puddle layer remained above critical limits, except for K, Zn and Mo (BARC and FRG, 2012). The rice cultivar in this study was BRRI Dhan28 (developed by Bangladesh Rice Research Institute); it is a predominant variety covering almost 33% of the total Boro rice area (out of 97%) cultivating modern varieties. The average yield, height and growth duration was 6 t $ha^{-1}$, 90 cm, and 140 days respectively, of which the vegetative