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Ground cover rice production systems increase soil carbon and nitrogen stocks at regional scale

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Abstract. Rice production is increasingly limited by water scarcity. Covering paddy rice soils with films (so-called ground cover rice production system: GCRPS) can significantly reduce water demand as well as overcome temperature limitations at the beginning of the growing season, which results in greater grain yields in relatively cold regions and also in those suffering from seasonal water shortages. However, it has been speculated that both increased soil aeration and temperature under GCRPS result in lower soil organic carbon and nitrogen stocks. Here we report on a regional-scale experiment conducted in Shiyan, a typical rice-producing mountainous area of China. We sampled paired adjacent paddy and GCRPS fields at 49 representative sites. Measured parameters included soil carbon (C) and nitrogen (N) stocks (to 1 m depth), soil physical and chemical properties, δ^{15}N composition of plants and soils, potential C mineralization rates, and soil organic carbon (SOC) fractions at all sampling sites. Root biomass was also quantified at one intensively monitored site.

The study showed that: (1) GCRPS increased SOC and N stocks 5–20 years following conversion from traditional paddy systems; (2) there were no differences between GCRPS and paddy systems in soil physical and chemical properties for the various soil depths, with the exception of soil bulk density; (3) GCRPS increased above-ground and root biomass in all soil layers down to a 40 cm depth; (4) δ^{15}N values were lower in soils and plant leaves indicating lower NH_3 volatilization losses from GCRPS than in paddy systems; and (5) GCRPS had lower C mineralization potential than that observed in paddy systems over a 200-day incubation period. Our results suggest that GCRPS is an innovative production technique that not only increases rice yields using less irrigation water, but that it also increases SOC and N stocks.

1 Introduction

Globally, more than 3 billion people depend on rice as a staple food (FAO, 2011). Water used for irrigation is becoming increasingly scarce due to growing water demands from increasing populations and economies across Asia and from projected climatic changes. It is expected that by 2025 about 15 million ha of irrigated rice, 27 million ha of rainfed rice, and nearly 20 million ha of rainfed upland rice will suffer from water scarcity worldwide (Bouman, 2007). An annual increase of about 8–10 million tons will be required to meet the global forecasted needs over the next 20 years (IRRI, 2011). In this scenario, water-saving technologies are urgently needed to cope with such rice production demands.

China is the world's largest rice producer with an average rice production rate of 197 million tons yr^{-1}, which in

2009 was grown on ca. 30 million hectares and accounted for 43.7 % of the total national cereal grain production (Fan et al., 2010). Water shortages already affect more than 4 million ha devoted to rice production in China, and a significant proportion of this area also shows comparatively low yields resulted from low-temperature limitations. One of the most promising techniques to overcome these limitations is the ground cover rice production system (GCRPS). Here, the soil is covered – typically with plastic film – to reduce evaporation, seepage losses and increase springtime soil temperatures. The soil is kept moist between irrigation periods thanks to the covering material, which reduces irrigation water demand by 50–90 % (Tao et al., 2015). The actual reduction in irrigation water demand is dependent on soil type, precipitation, and cultivation duration (Tao et al., 2006; Liu et al., 2003). Furthermore, high-yielding lowland rice varieties (middle-duration cultivar, about 140 days) can still be grown in upland locations using GCRPS, which results in similar or even greater yields than paddy systems (Qu et al., 2012; Liu et al., 2013, 2014; Tao et al., 2015). Thus, GCRPS is consistent with China's 12th Five Year Plan that requires development of technologies to reduce the water demand and greenhouse gas emissions (GHG) in agricultural production (Yao et al., 2014; Tao et al., 2015).

Improving rice production systems should not be solely focused on increasing productivity, but should also consider other aspects affecting sustainability, such as preservation of optimal levels of soil organic carbon (SOC) and total N. Soil organic matter (SOM) helps to maintain soil structure and fertility, decreases the risk of soil erosion and degradation (Watts et al., 2006; Powlson et al., 2011), provides nutrients to plants and soil microbes (Tiessen et al., 1994), and increases soil water holding capacity, thereby improving the systems' ability to resist drought stress (Rawls et al., 2003). The sustainability of a production system tends to be correlated with the maintenance or increase of SOM stocks, which tends to lead to increased yield potentials worldwide (Lehmann et al., 2007). The amount of organic C stored in a soil is a fine balance between organic C inputs, mineralization, and lateral exports (Jenny, 1941; Amundson, 2001). These processes are strongly affected by temperature, water available to plants, soil mineral composition, and the chemical properties of the precursor biomass (Swift, 2001; Saiz et al., 2012).

Compared to upland cereal production systems, submerged paddy rice cultivation is considered to be a sustainable cropping system because the permanent presence of water results in anoxic conditions that drive soil redox potential to the lowest natural levels (Gao et al., 2008; Pan et al., 2010). It is widely acknowledged that decomposition of SOM is slower in submerged soils than in aerated soils (Sahrawat, 2004), and previous studies have shown that continuous rice cropping on submerged soils may favor the maintenance, and even the increase of SOM stocks (Cassman et al., 1995; Bronson et al., 1997; Witt et al., 2000). Consequently, it has been hypothesized that the absence of permanently anaerobic conditions, in conjunction with increased soil temperatures under GCRPS cultivation may result in either unchanged or increased SOC losses as a result of potentially enhanced microbial decomposition (Pan et al., 2003, 2010; Qu et al., 2012). Indeed, earlier studies showed trends towards lower SOC and total N stocks in fields using the plastic film-based GCRPS technique. However, these studies only investigated the topsoil (0–20 cm) above the hardpan at a single experimental site (Li et al., 2007; Fan et al., 2012; Qu et al., 2012). The GCRPS-induced shift from flooded soils to higher aeration and soil temperatures at the start of the growing season may result in reduced CH_4 emissions, while N_2O emissions (Kreye et al., 2007; Yao et al., 2014) and C mineralization rates may increase (Koch et al., 2007). On the other hand, high ammonia volatilization in paddy systems tends to result in low N use efficiency (approx. 30 %) (Ju et al., 2009) and covering the soil surface might reduce ammonia volatilization rates, increase fertilizer use efficiency, plant biomass and/or soil N stocks. Furthermore, variable soil water regimes such as that observed under GCRPS cultivation can increase root biomass (Thakur et al., 2011; Uga et al., 2013), which in turn could promote C inputs into the soil. A thorough regional-scale evaluation of GCRPS effects on SOC and total N stocks is needed to address these effects, but has not yet been reported.

To evaluate the impact of GCRPS on soil C and N stocks as well as identifying the primary N loss pathways from GCRPS and paddy systems using the natural abundances of ^{15}N, we conducted a field study sampling 49 pairs of neighboring GCRPS and paddy fields in the Shiyan region, central China, where the GCRPS technique was first introduced approximately 20 years ago. We hypothesized that decreased soil moisture conditions and increased soil temperature and redox potential in GCRPS would stimulate soil C and N mineralization, leading to an overall reduction of soil C and N stocks under GCRPS at a regional scale.

2 Materials and methods

2.1 Sampling region characteristics

The study was situated in the Shiyan region, Hubei province, central China (32°02′ to 33°10′ N, 109°44′ to 111°04′ E; 169 m to 661 m a.s.l.; see Supplement Table S1), where GCRPS was introduced at the end of the last century (Shen et al., 1997; Liang et al., 1999). Shiyan is located in the QinBaShan Mountains with peaks reaching a maximum altitude of 2740 m a.s.l. The area is in the northern subtropical agro-climatic zone of China's eastern monsoon region (Smit and Cai, 1996). Low temperatures at the start of the growing season together with severe seasonal water scarcity often limit rice production in these mountainous regions (Shen et al., 1997). The mean annual temperature and rainfall (cal-

culated for the 1961–2009 period from seven meteorological stations located in the respective counties of Shiyan) are 15.3 °C and 829 mm, respectively (Zhu et al., 2010). There is little inter-annual variation in temperature and rainfall (coefficient of variations of 0.01 and 0.05). Annual rainfall patterns show pronounced seasonality, with approximately 45 % (375 mm) of the rainfall occurring during the summer period (June to August). The mean total sunshine hours per year is 1835 h (Zhu et al., 2010). Traditional lowland rice cultivation (paddy) and GCRPS are spatially interwoven, because only some farmers adopted GCRPS after its invention 2 decades ago. This limited adoption is due to the implications GCRPS cultivation has on farming activities, labor demand, and associated costs (Zhou et al., 2008). In most cases the adoption of GCRPS by individual farmers was documented by the local administration so it was possible to trace specific land management records for the selected sites and fields.

2.2 Site and field selection

Site selection was performed by experienced staff members from the Department of Agriculture in Shiyan and extension personnel who have been working closely with farmers at the individual local villages. Specific attention was paid to ensure proper representativeness of the different rice-growing areas (i.e., varying altitudes, contrasting soil types, and proper coverage of the range of time since adoption of GCRPS). Information on fertilizer use, and soil and crop management was obtained through farmer interviews (Table S2). Topdressing is not used in GCRPS since the plastic film covers the soil surface; rather the farmers usually broadcast all the fertilizer before transplanting (Liu et al., 2013). The day before transplanting, a compound NPK fertilizer and urea were applied to the soil surface in a single dose and incorporated into the soil by ploughing. The total N input was about 150 kg N ha^{-1} for GCRPS. The soil surface was then leveled and covered with a transparent film 5 µm thick (Liu et al., 2013). For paddy systems, an average of 100 kg N ha^{-1} was applied as a compound NPK fertilizer to the soil surface and incorporated to a depth of 20 cm before transplanting. At tillering and grain filling stages, additional doses of 40 kg N ha^{-1} were given as urea in order to increase rice-milling quality, protein content (Wopereis-Pura et al., 2002; Leesawatwong et al., 2005), and yield. This resulted in a total N application rate of approximately 180 kg N ha^{-1} for the paddy rice system.

We compared, across a region of 5000 km^2, 49 pairs of neighboring fields that were managed either as traditional paddy rice fields or where GCRPS had been applied continuously for 5–20 years. A total of 49 sites with paired treatments consisting of GCRPS vs permanent flooding paddy fields were selected for soil and plant sampling. Regardless of the current production system, all sites had been growing rice for more than 40 years. The distance between the paired plots was less than 100 m in most cases, with only 9 out of 49 paired plots being more than 250 m apart (Table S1). Geographical coordinates of the sites and fields were recorded by GPS (Garmin Colorado 300) and altitudes were obtained using the global digital elevation model (GDEM) provided by NASA and METI (2008).

2.3 Sampling methodology and analytical procedure

Soil samples from the 49 paired sites were collected before field preparation during March and April 2011. These sites represented a wide range of different soil types (Table S1). At each of the 98 fields, six to nine spatial replicates were taken with the aid of a soil corer (3.5 cm diameter) at four depths intervals (0–20, 20–40, 40–60, and 70–90 cm). Additionally, three replicate samples were collected from each soil profile excavated in each field for each depth and analyzed for bulk density (Blake and Hartge, 1986) and soil texture (Gee, 1986).

Soil samples for each depth interval were air-dried for 5 days and sieved to 2 mm. Identifiable plant material (> 2 mm) was removed during sieving. Soil pH (Mc Lean, 1982) was measured in a 1 : 2.5 soil-water solution using a combined electrode pH meter (HI 98121, Hanna Instruments, Kehl am Rhein, Germany). Extractable soil NO_3^--N and NH_4^+-N (Keeney and Nelson, 1982) was estimated from 1 : 10 soil-$CaCl_2$ (0.01 M) extracts using an AutoAnalyzer (AA3, Bran & Luebbe, Nordstadt, Germany). Sub-samples for the determination of soil C and N concentration and ^{15}N isotope natural abundance were powdered in a ball mill (MM200, Retsch, Haan, Germany) with the soil carbonates removed prior to C analyses (Harris et al., 2001; Walthert et al., 2010). Analyses were conducted using a Costech elemental analyzer (Costech International S.p.A., Milan, Italy) fitted with a Zero Blank autosampler coupled via a ConFloIII to a Thermo Finnigan Delta V Plus isotope ratio mass spectrometer (Thermo Scientific, Waltham, MA, USA). Soil C and N stocks were calculated using element concentrations and bulk density data for all sites.

Leaves at maximum tillering stage and aboveground plant biomass at maturity stage were sampled from 36 paired sites (at some sites rice was not planted as foreseen, due to a severe drought) with three replicates from each site used for analysis of ^{15}N natural abundance using a CN analyzer coupled to a mass spectrometer (see above). Carbon and N concentrations were then determined by an elemental analyzer (EA1108). Carbon and N assimilated in aboveground biomass were calculated as the sum of grain and straw dry matter multiplied by grain and straw C or N concentration at harvest.

Root biomass was quantified at a long-term experimental site in Fang County (32°07′ N, 110°43′ E; Fig. S1 in the Supplement; Tao et al., 2015) where 22 paired GCRPS and paddy sites were located (Table S1). The site consists of the two production systems (paddy and GCRPS) and two N fertilizer application rates (0, 150 kg N ha^{-1}) in three-fold replication. All 12 subplots (8.5 m × 9.5 m) were arranged in a com-

pletely randomized block design. Root biomass was quantified for three replicate cores in each of the subplots. For this purpose, soil columns (40 cm height and 15 cm diameter) were collected at the maximum tillering stage using stainless steel cylinders. The soil column was separated into depth intervals of 0–10, 10–20, and 20–40 cm. Soil samples were placed in mesh bags and set in a water stream to remove soil particles and then cleaned by tap water on a 0.2 mm mesh. Cleaned root samples in different soil depths were transferred into small envelopes and oven-dried at 75 °C for 24 h.

Potential soil C mineralization rates from all 49 paired paddy and GCRPS sites were determined using a laboratory incubation assay. Three soil samples with a volume of 20 cm × 10 cm × 20 cm (depth) were sampled at each site using a spade. Samples were composited and air-dried. Three replicates with 30 g of soils were incubated for 200 days at 25 °C at 60 % soil water-holding capacity in 150 mL bottles. CO_2 fluxes were measured daily for the first 10 days, then every 3 days for the following 3 weeks and then every 1–2 weeks afterwards. The gas measurement period was from 5 min to 4 h depending on CO_2 flux rates. For flux measurements, the jars were closed gas-tight and CO_2 headspace concentrations were measured with a non-dispersive infrared sensor (Premier, Dynament, United Kingdom) at 10 s intervals. CO_2 fluxes were calculated from concentration changes with time, considering headspace volume, temperature, and air pressure. Total cumulative emissions were obtained by summing the measured daily fluxes using trapezoidal integration assuming a linear change in flux between measurements.

Organic matter (OM) fractions were physically separated before and after incubation using a slightly modified procedure to that described in Zimmermann et al. (2007). Briefly, 30 g of dried soil (< 2 mm) were added to 161 mL water and dispersed by means of a calibrated ultrasonic probe (Labsonic 2000, B Braun, Melsungen, Germany) using a light output energy (22 J ml^{-1}). The dispersed suspension was then wet sieved over a 53 µm mesh size until clear rinsing water was achieved. The fraction > 53 µm was dried at 40 °C and weighed. This fraction contained sand-size particles and aggregates (heavy fraction; HF), as well as particulate organic matter (light fraction; LF). These two fractions were separated using the procedure for recovery of organic matter from soils using static dense media as described in Wurster et al. (2010). The dried fraction > 53 µm was stirred in a water / sodium polytungstate solution with a density of 1.87 g cm^{-3}. The mixture was centrifuged at 1000 g for 15 min, and allowed to settle overnight prior to freezing. The LF was subsequently decanted and both fractions were then washed with deionized water, dried at 40 °C, and weighed. The solution < 53 µm (silt and clay) was filtered through a 0.45 µm membrane filter and the material retained in the membrane (s+c) was then dried at 40 °C and weighed. An aliquot of the filtrate was frozen to determine the amount of dissolved organic carbon (DOC) using a C / N liquid analyzer (Multi N/C® 3100 Analytik Jena, Jena, Germany).

2.4 Statistical analyses

All statistical analysis and calculations were performed in the Statistics Analysis System (SAS, version 8.2). Shapiro–Wilk tests were applied to check for normal distribution. Non-parametric tests were applied if the data were not normally distributed. Before any statistical test was performed, we tested for significant differences between GCRPS and paddy sites according to a model that included soil type, years since conversion, soil type, and elevation as potential variables influencing the percentage change of SOC / N stocks between both systems. However, we found that the percentage change of SOC / N stocks was not significantly affected by soil type, years since conversion, elevation, nor by any of the interactions. Therefore, we pooled over different soil types, years since conversion, and elevation in the subsequent statistical analysis (Table S3). A paired *t* test was used to test for differences in soil texture (clay, silt, and sand content), bulk density, pH, and mineral N concentrations (Nmin) between GCRPS and paddy sites. All statistical analyses and calculations were performed using parametric (paired and two-tailed t-test, Pearson chi-square) and non-parametric (Wilcoxon matched pairs rank sum test; two-tailed) tests. Differences in root biomass between the two systems were tested using a general linear model (GLM) procedure. Results are expressed as arithmetic means ± standard error of the means. Levels of significance at 0.001, 0.01, and 0.05 probability were used, denoted by ∗∗∗, ∗∗, and ∗, respectively. Results which were not significant were denoted by *ns*.

3 Results

Average SOC concentrations and stocks were higher in GCRPS than in paddy sites for each soil depth interval except for the top layer (0–20 cm; Fig. 1a, c; see Table S4 for details). Similarly, total N concentrations and stocks over the 1m profile also tended to be larger in GCRPS than in paddy sites, although significant differences were only observed in the 20–40 cm depth interval (Fig. 1b, d; Table S4). There were no detectable differences in soil texture (Fig. 2a, b, c; Table S4), pH, or mineral N content (Fig. 2e, f; Table S4) between GCRPS and paddy sites for any soil depth interval. Soil bulk density (Fig. 2d; Table S4) tended to be lower in GCRPS than in paddy sites over the 1 m soil profile, although significant differences were only found in the 20–40 cm depth interval ($P < 0.0001$).

Mean C and N assimilation rates in aboveground biomass at maturity were higher in GCRPS than in paddy sites (Fig. 3; $P < 0.0001$, $= 0.0002$ for C and N). Root biomass from the one selected site was significantly affected by the production

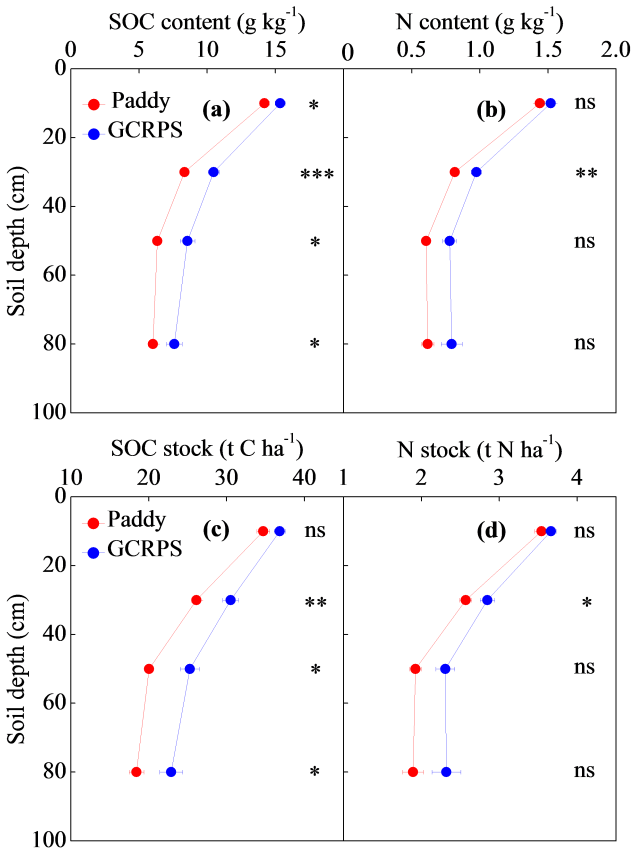

Figure 1. Concentrations and stocks of soil organic carbon and total nitrogen in traditional paddy fields and GCRPS at different soil depths. Data presented are the mean values pooled over 49 paired sites (for 0–20 and 20–40 cm, n is 147; for 40–60 cm, n is 108; and for 70–90 cm, n is 63). Errors bars indicate the standard error of the means. $***$, $**$, and $*$ denote significance at 0.001, 0.01, and 0.05 probability levels, respectively. Values that are not significant are denoted by ns.

system, but not by N fertilizer rates or by the interaction of the production system and N fertilization (Fig. 4; Table S4). Pooled over the two N fertilizer rates, the root biomass at maximum tillering stage was significantly greater in GCRPS than in paddy sites for all depth intervals down to 40 cm depth (Fig. 4).

Potential C mineralization rates did not differ between GCRPS and paddy sites (data not shown), although paddy soils showed a tendency towards higher cumulative C loss compared to GCRPS over the 200-day incubation period (Fig. 5). For the GCRPS, the SOC contents of the various fractions were similar before and after the incubation experiment (Fig. 6). However for the paddy treatment, the amount of SOC in the heavy fraction was significantly lower after incubation compared to before the incubation ($P < 0.05$). No differences were found in the s+c, LF, and DOC fractions before and after the incubation (Fig. 6).

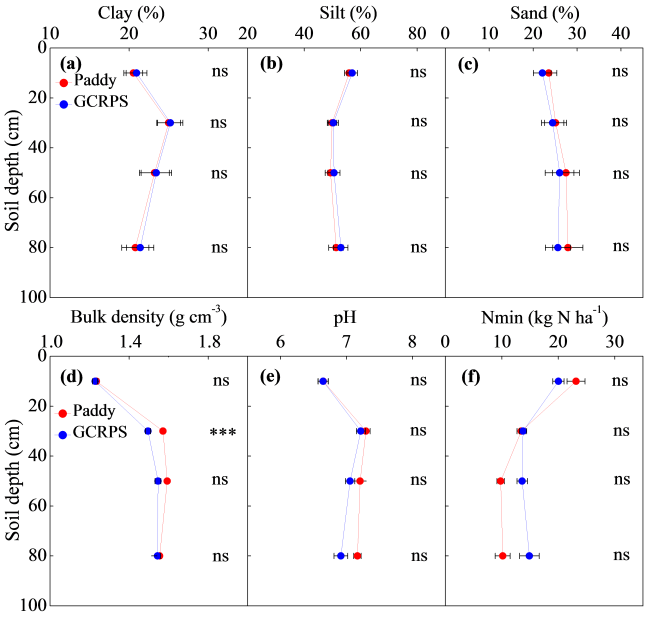

Figure 2. Average soil clay, silt, and sand contents (for 0–20 and 20–40 cm, n is 49; for 40–60 cm, n is 36; and for 70–90 cm, n is 21), soil bulk density, pH, and mineral nitrogen concentrations (N_{min}; for 0–20 and 20–40 cm, n is 147; for 40–60 cm, n is 108; and for 70–90 cm, n is 63) at different soil depths from 49 paired sites cultivated either under traditional paddy fields or GCRPS. Errors bars indicate SEM (standard error of the mean) and $***$ denotes significance at a 0.001 probability level. Values that are not significant are denoted by ns.

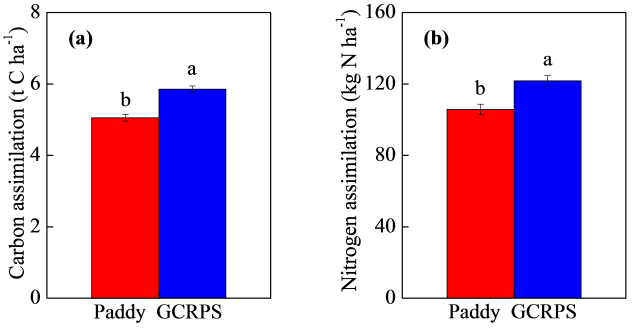

Figure 3. Carbon and nitrogen assimilated in aboveground biomass at maturity (n is 108). Data presented are the means pooled over 36 paired sites (these represent all the sites where rice was grown in 2011) with three replicates at each site. Errors bars indicate SEM. Bars labeled with different lowercase letters indicate statistically significant differences ($P < 0.05$) between paddy sites and GCRPS.

Mean soil $\delta^{15}N$ signatures were lower in GCRPS than in paddy sites at each depth interval (Fig. 7a; Table S4). The average $\delta^{15}N$ signature in plant leaves was also lower ($P < 0.0001$) in GCRPS compared to paddy fields at maximum tillering stage (Fig. 7b). Ln-transformed soil N concen-

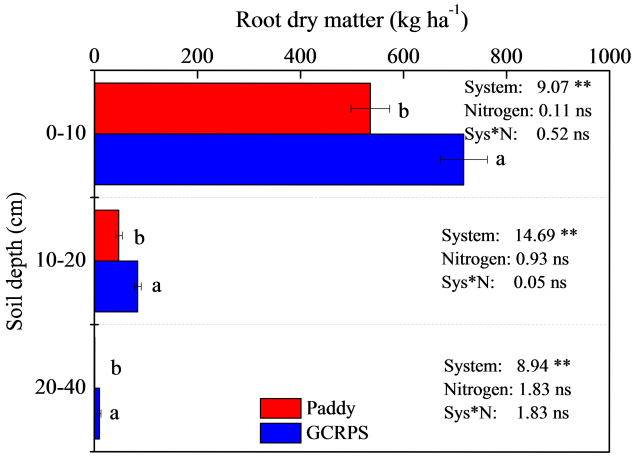

Figure 4. Root dry matter at maximum tillering stage for different soil depths in traditional paddy fields and GCRPS. *n* is 18 and error bars denote SEM. Bars labeled with different lowercase letters indicate differences ($P < 0.05$) between paddy sites and GCRPS.

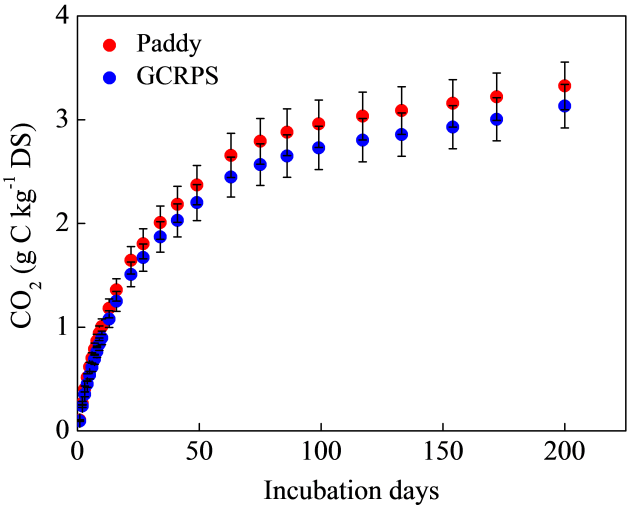

Figure 5. Differences in cumulative organic carbon mineralization during a 200-day incubation period of top soils (0–20 cm) collected from either paddy sites or GCRPS. Data presented are the mean values pooled over 49 paired sites. Error bars indicate SEM.

trations were inversely correlated with corresponding δ^{15}N values in either GCRPS or paddy sites (Fig. 8).

4 Discussion

Here, we provide a thorough regional-scale evaluation of GCRPS effects on SOC and total N stocks, based on sampling of cultivated fields at 49 paired sites (i.e., adjacent sites experiencing comparable soil and environmental conditions, Figs. 2 and S1 and Tables S1 and S4) down to 1 m depth across an entire geographical region. Our results show that within the sampling region, conversion of paddy fields to GCRPS increased SOC concentrations (Fig. 1a; Table S4) and storage (Fig. 1c; Table S4) after 5 years since the time of conversion. We were able to identify two main processes that contributed to the positive effect of GCRPS on SOC stocks.

(a) Increased above- and belowground carbon inputs. Plant residues and organic fertilizers directly affect the amount and quality of organic matter above the hardpan (between 20 and 40 cm), while the accumulation and stabilization of subsoil OM in these agricultural systems derives mainly from dissolved OM leached from the plough layer (Tanji et al., 2003). In our study we observed larger aboveground biomass and grain yields for GCRPS compared to traditional paddy fields (Fig. 3; Liu et al., 2013). Furthermore, root biomass was also found to be greater under GCRPS cultivation in all soil layers down to 40 cm depth (Fig. 4; Table S4).

Recent literature has confirmed that rice cultivation under variable soil water regimes such as GCRPS results both in higher root biomass (Thakur et al., 2011; Uga et al., 2013), and more rhizodeposits (Tian et al., 2013) compared to traditional flooded paddy fields, likely because the larger above-

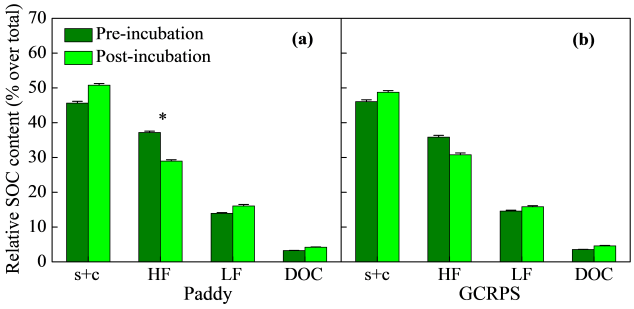

Figure 6. Relative SOC fractionation (% of total) of topsoils (0–20 cm) from either paddy sites or GCRPS-grown rice fields for the different physically separated fractions before and after a 200-day incubation period. s+c is fraction < 53 µm, HF/LF represent heavy/light fraction > 53 µm, and DOC represents dissolved organic carbon < 0.45 µm. For GCRPS, *n* is 18 and for paddy sites, *n* is 18 (random selection of 18 out of 49 paired sites). Error bars denote SEM. The asterisk indicates significant differences between pre- and post-incubation ($P < 0.05$).

ground biomass and grain yields require a larger root system to absorb more nutrients from the soil (Liu et al., 2003). GCRPS also promotes increased soil NO_3^- concentrations that can lead to more balanced plant N nutrition (NO_3^- and NH_4^+), which is beneficial for crop growth (Nacry et al., 2013). Moreover, the fluctuating soil water content inherent to GCRPS, which varies between 80 and 90 % water holding capacity (WHC), can limit the accessibility to some micronutrients (e.g., Mn, Fe) in the topsoil if they are oxidized to forms that cannot be directly assimilated by the plant (Tao et al., 2007; Kreye et al., 2009). For example, the lack of standing water may cause increased soil aeration, and thus,

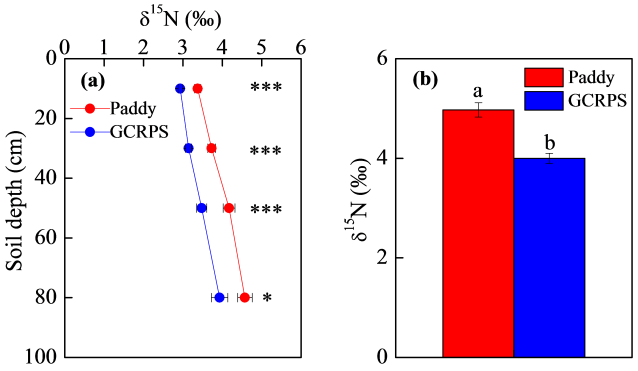

Figure 7. (a) Soil δ^{15}N isotopic signature in traditional paddy fields and GCRPS at different soil depths. Data presented are the mean values pooled over 49 paired sites (for 0–20 and 20–40 cm, n is 147; for 40–60 cm, n is 108; and for 70–90 cm, n is 63). **(b)** δ^{15}N signature in plant leaves at maximum tillering stage. Data presented are the means pooled over 36 paired sites (these represent all the sites where rice was grown in 2011) with three replicates at each site; n is 108. Errors bars indicate the SEM. $***$, $**$, and $*$ denote significance at 0.001, 0.01, and 0.05 probability levels, respectively. Values that are not significant are denoted by ns. Bars labeled with different lowercase letters indicate differences ($P < 0.05$) between paddy fields and GCRPS.

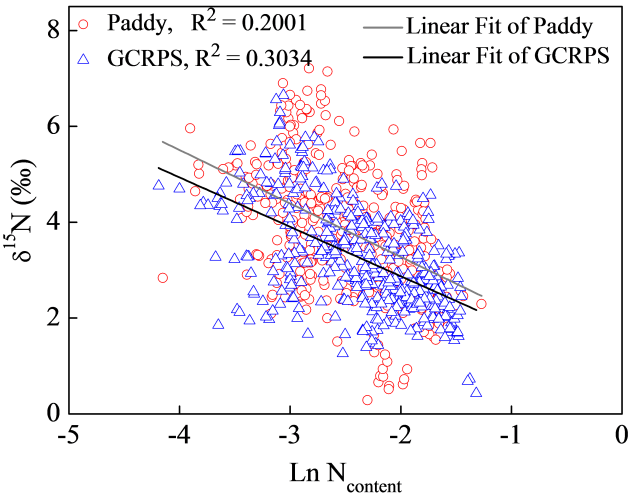

Figure 8. Correlation of δ^{15}N with Ln-transformed soil total nitrogen content up to 1 m depth. Data presented are all the individual samples measured across the 49 paired sites, which consist of three replicates for each site (n is 465).

higher redox potentials (Tao et al., 2007), resulting in the oxidized form of Mn that greatly lowers its availability to the plant (Norvell, 1988). Therefore, rice plants in GCRPS need to develop stronger root systems capable of accessing deeper soil layers to obtain a balanced micro-nutrient supply. Even if just a few fine roots penetrate the hardpan they may represent a large difference in deep SOC storage, as root channels may further promote percolation of organic compounds into the subsoil.

(b) Greater physical protection of soil organic matter against microbial degradation.

We conducted soil incubations under controlled environmental conditions using soils from all field sites to test whether GCRPS would enhance SOM stabilization or increase C mineralization, promoting net losses of SOM (Xiong et al., 2014). Our results showed no significant differences in mineralization rates between soils from the GCRPS and paddy systems for all measuring dates over a 200-day incubation, although cumulative C losses over the entire incubation period were consistently greater for paddy soils (Fig. 5). This could suggest that SOM in fields managed under GCRPS may be more effectively preserved than SOM in traditional paddy systems. Besides the physicochemical protection offered by clay minerals (Koegel-Knabner et al., 2010; Saiz et al., 2012), other stabilizing mechanisms could be conferred through higher OM inputs resultant from enhanced above and belowground biomass production, as higher OM input rates are known to promote stable micro- and mesoaggregates (Six et al., 2004). However, we did not observe significant differences between both systems in the physically protected fractions for the topmost soil layer (Fig. 6). It is likely though, that aggregation and/or stabilization might become more relevant at deeper locations where the differences in SOC concentrations were greater. Indeed, the strong anaerobiosis and stabilization conditions prevailing at greater depths would likely promote OM accumulation below the hardpan, as we found in our study (Fig. 1; Koegel-Knabner et al., 2010). Also relevant within this context is the contrasting soil redox conditions observed between the two systems (Liu et al., 2013). The more frequent oscillation in redox conditions (aerobic to anaerobic and back) in GCRPS may have a strong positive influence on the generation of organo-mineral complexes, which are of paramount importance for the stabilization of OM in paddy soils (Koegel-Knabner et al., 2010).

Similar to SOC concentrations and stocks, soil organic N concentrations and stocks were larger in GCRPS than in paddy fields over the 1m soil profile. However, significant differences were only observed in the 20–40 cm depth interval (Fig. 1b, d). In addition, we observed δ^{15}N enrichment in paddy soils for all soil depths (Fig. 7a), which was also reflected in the plant biomass (Fig. 7b). Bulk soil δ^{15}N is a combined signal for organic and mineral N compounds and may be affected by (1) the amount and isotopic signature of applied fertilizer (Yun et al., 2011), (2) isotopic fractionation occurring during N cycle processes, such as N mineralization, nitrification, and assimilation (Bedard-Haughn et al., 2003), and (3) ^{15}N depletion of gaseous N compounds produced during denitrification and ammonia volatilization with subsequent ^{15}N enrichment of the remaining soil N (Bedard-Haughn et al., 2003). Based on farmers' interviews, the dominant fertilizer used was a compound NPK fertilizer with urea as the N form (δ^{15}N of ca. 0.5 ‰) (Yun et al.,

2011). As well as urea-N, 11 of the 98 sites received manure ($\delta^{15}N > 10$ ‰). Most crucially, N fertilization rates were comparable for both management systems (GCRPS: approx. 150 kg N ha^{-1}; paddy soils: approx. 180 kg N ha^{-1}). Therefore, kinetic isotope fractionation processes in the soil rather than mixing of different N sources with distinct $\delta^{15}N$ signatures likely account for the observed differences in soil $\delta^{15}N$. This is confirmed by the observation that Ln-transformed soil N concentrations were inversely correlated with the $\delta^{15}N$ values (Fig. 8).

The largest fractionation factors are consistently reported for gaseous N losses (Bedard-Haughn et al., 2003; Robinson, 2001) so it is likely that changes in N_2, N_2O, NO, and NH_3 losses account for the ^{15}N enrichment in paddy soils. Nitrification- and denitrification- induced losses of N_2, N_2O, and NO were expected to increase under unsaturated soils typical for GCRPS cultivation as compared to continuous flooding of paddy soils that has also been documented in earlier studies (Kreye et al., 2007; Yao et al., 2014). Therefore, we can rule out both fertilizer effects and changes in denitrification losses as significant factors explaining lower $\delta^{15}N$ in GCRPS soils. The ^{15}N enrichment in paddy soils and increased soil N stocks under GCRPS are therefore more likely related to ammonia volatilization following fertilizer application. Ammonia loss from urea fertilization in paddy rice fields can be very high with emission factors ranging from 9–40 % of applied N (Xu et al., 2013). Covering the soil with a plastic film immediately after fertilizer application (Zhuang and Wang, 2010) or manure deposits (Webb et al., 2013) greatly reduces NH_3 volatilization losses. Therefore, we expect that the greater soil N stocks in GCRPS fields were associated with decreased NH_3 volatilization.

5 Conclusion

We demonstrate for the first time, across a wide range of spatially representative paired sites under real farming conditions, that GCRPS significantly increased soil organic C and total N stocks under varying edaphic conditions. GCRPS also increased above- and belowground root biomass in all soil layers down to 40 cm depth. This indicates that GCRPS is a stable and sustainable technique that maintains key soil functions, while increasing rice yield and expanding the cultivation of a valuable crop into regions where it has been hampered by low seasonal temperatures and/or a lack of irrigation water. However, the use of plastic sheets as cover material remains an obstacle because plastic residues often remain in the field and pollute the environment. Biologically degradable films may be a suitable solution to overcome this problem, and supplying such films with micronutrients may allow a more effective and integrated nutrient management that could further boost grain yields.

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