Biogeosciences Discuss., 12, 3647–3674, 2015
www.biogeosciences-discuss.net/12/3647/2015/
doi:10.5194/bgd-12-3647-2015

Biogeosciences Discussions
Open Access

Ground cover rice production system facilitates soil carbon and nitrogen stocks at regional scale

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Received: 4 January 2015 – Accepted: 3 February 2015 – Published: 27 February 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

BGD
12, 3647–3674, 2015

Abstract

Rice production is increasingly challenged by irrigation water scarcity, however covering paddy rice soils with films (ground cover rice production system: GCRPS) can significantly reduce water demand as well as overcome temperature limitations at the beginning of the vegetation period resulting in increased grain yields in colder regions of rice production with seasonal water shortages. It has been speculated that the increased soil aeration and temperature under GCRPS may result in losses of soil organic carbon and nitrogen stocks. Here we report on a regional scale experiment, conducted by sampling paired adjacent Paddy and GCRPS fields at 49 representative sites in the Shiyan region, which is typical for many mountainous areas across China. Parameters evaluated included soil C and N stocks, soil physical and chemical properties, potential carbon mineralization rates, fractions of soil organic carbon and stable carbon isotopic composition of plant leaves. Furthermore, root biomass was quantified at maximum tillering stage at one of our paired sites.

Against expectations the study showed that: (1) GCRPS significantly increased soil organic C and N stocks 5–20 years following conversion of production systems, (2) there were no differences between GCRPS and Paddy in soil physical and chemical properties for the various soil depths with the exception of soil bulk density, (3) GCRPS had lower mineralization potential for soil organic C compared with Paddy over the incubation period, (4) GCRPS showed lower $\delta^{15}N$ in the soils and plant leafs indicating less NH_3 volatilization in GCRPS than in Paddy; and (5) GCRPS increased yields and root biomass in all soil layers down to 40 cm depth. Our results suggest that GCRPS is an innovative rice production technique that not only increases yields using less irrigation water, but that it also is environmentally beneficial due to increased soil C and N stocks at regional scale.

BGD
12, 3647–3674, 2015

1 Introduction

Globally more than 3 billion people depend on rice as a staple food (FAOSTAT, 2011). China is the world's largest rice producer, with an average rice production rate of 197 million t yr^{-1}, grown on approximately 29.9 million ha in 2009, and accounts for 43.7 % of the total national cereal grain production (Fan et al., 2010). With growing populations and economies in Asia and in view of ongoing climatic changes, irrigation water is becoming increasingly scarce. 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 (Bouman, 2007). However, in order to meet forecasted needs globally over the next 20 years, an annual of 8–10 million t production increasing must be produced (IRRI, 2011). Therefore, water-saving technologies are urgently proposed for the future rice production worldwide.

Within China, water shortages and temperature limitations already affect more than 4 million ha of rice production and 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 spring-time soil temperatures. The soil is kept moist between irrigation periods by the covering material, reducing water demand by 50–90 %. As with conventional paddy rice systems (Paddy), high-yielding lowland rice varieties can still be grown using GCRPS resulting in similar or even greater yields as compared to Paddy systems (Qu et al., 2012; Liu et al., 2013, 2014). Thus, GCRPS is well in line with China's 12th Five Year Plan that requires development and technologies to reduce the water demand and environmental footprint of agricultural production.

Improving rice production systems should not be solely focused on increasing productivity however, but should also be linked to other factors affecting the stability and sustainability of production, such as soil organic C and total N. On a global scale, optimal soil organic matter contents maintain and improve soil structure and fertility, decrease risks of erosion and soil degradation (Watts et al., 2006; Powlson et al., 2011),

BGD
12, 3647–3674, 2015

provide nutrients to plants and soil microbial populations (Tiessen et al., 1994) and increase the water holding capacity thereby improving the ability of soils to resist drought stress (Rawls et al., 2003).

The sustainability of a production system tends to be correlated with maintaining or increasing soil organic matter content and also tends to result in increased yield potential worldwide (Lehmann, 2007). Submerged paddy rice system is considered to be a stable and sustainable cropping system compared with upland systems because the submergence results in the depletion of soil O_2 by microorganisms driving the soil redox potential to the lowest natural levels (Gao et al., 2004; Pan et al., 2010). It is widely acknowledged that decomposition of plant residues and other organic matter is slower in submerged than in aerated soil (Acharya, 1935), and previous studies have shown that continuous rice cropping on submerged soils and prolonged soil submergence favours the maintenance or increase of soil organic matter (SOM) (Cassman et al., 1995; Bronson et al., 1997; Witt et al., 2000).

Previous research has already demonstrated that the water-saving GCRPS technique increased both grain yields and water-use efficiency in areas where seasonal water shortages and/or low temperatures during early growth stages were the main limiting factors for rice production (Qu et al., 2012; Liu et al., 2013, 2014). The GCRPS also minimized the effects of varying edaphic conditions on yields at a regional scale (Liu et al., 2013). However, a regional-scale evaluation of GCRPS effects on soil organic C and total N stocks has not yet been reported. Although the shift from flooded, anaerobic paddy soils to higher aeration and soil temperatures at the start of the growing season may result in reduced CH_4 emissions, N_2O emissions (Kreye et al., 2007) and mineralization rates of soil organic C (SOC) stocks may increase (Stanford et al., 1973). We hypothesized that optimal soil moisture and increased soil temperature and redox potential would stimulate soil C and N mineralization, leading to a reduction in soil C and N stocks under GCRPS at a regional scale. In the long-term this will affect soil fertility and nutrient retention and threaten the stability and sustainability of GCRPS production systems.

BGD
12, 3647–3674, 2015

To evaluate the environmental consequences of GCRPS on soil C and N stocks, we conducted a field study in Shiyan County, Central China, where the GCRPS technique was first introduced approximately 20 years ago due to water and temperature limitations of rice cultivation (Zhou et al., 2008). In our study we compared 49 pairs of neighbouring farmer fields across a cultivation region of 5000 km^2 that were managed either as traditional paddy rice fields or where GCRPS has been introduced and applied continuously for 5–20 years.

2 Materials and methods

2.1 Sampling region characteristics

The study was situated in Shiyan region, Hubei province, Central China (32°02′ to 33°10′ N, 109°44′ to 111°04′ E, see 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. According to Smit and Cai (1996) this area is in the northern subtropical agro-climatic zone of China's eastern monsoon region. Low temperatures at the start of the growing season and severe seasonal and regional water scarcity often limit rice production in these mountainous regions (Shen et al., 1997). The mean annual temperature and total average annual rainfall (calculated for the 1961–2009 period from seven meteorological stations located in the respective counties of Shiyan) is 15.3 °C and 829 mm (Zhou et al., 2008). Annual rainfall patterns show pronounced seasonality, with approximately 45 % of the rainfall occurring during the summer period (June to August). The total sunshine hours per year are 1835. Given that GCRPS has only been introduced two decades ago and this growing technique has implications for farming activities, labour demand and costs, GCRPS and traditional lowland rice cultivation are often spatially interwoven, i.e. some farmers have adopted the technique while others have not (Zhou et al., 2008). However, in most cases the adoption of GCRPS by individual farmers is

BGD
12, 3647–3674, 2015

well documented by the local administration so that 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 local Agricultural Bureau in Shiyan, with specific attention being paid to cover different rice growing areas at varying altitudes, on contrasting soil types and over a range of time spans since adoption of the GCRPS technique. Information on soil and crop management, was obtained through farmer interviews. GCRPS fields received compound fertilizer containing approx. 150 kg N ha^{-1} and Paddy fields received compound fertilizer containing approx. 180 kg fertilizer N ha^{-1} in applications. A total of 49 sites with paired treatments consisting of GCRPS vs. permanent flooding paddy fields (hereafter referred to as GCRPS and Paddy) were selected for soil and plant sampling. The distance between the paired plots were in most cases less than 100 m 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 49 paired GCRPS vs. Paddy sites were collected before field preparation during March to April 2011 across Shiyan County, Hubei province (32°02′ to 33°10′ N, 109°44′ to 111°04′ E) of Central China. These sites represented a wide range of different soil types. 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, 70–90 cm). Furthermore, three replicate samples were collected from each soil profile excavated in each field for each depth and analysed 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 grounded by hand to pass a 2.0 mm sieve; identifiable plant

BGD
12, 3647–3674, 2015

material (> 2.0 mm) was removed during sieving. These samples were used for analysis of physical and chemical soil properties. Soil pH was measured in 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 was estimated from 1 : 10 soil-$CaCl_2$ (0.01 M) extracts using an autoanalyser (AA3, Bran & Luebbe, Nordstadt Germany). Sub-samples for determination of soil C and N content and ^{15}N and ^{13}C isotope natural abundance were powdered in a ball mill (MM200, Retsch, Haan Germany) and had 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., Milano, Italy) fitted with a zero-blank auto-sampler 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 concentrations and bulk density data for all sites.

The latest expanded 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 the content and ^{15}N natural abundance using a CN analyser coupled to a mass spectrometer (see above).

Potential carbon mineralization rates for 0–20 cm soil depth samples from all 49 paired Paddy and GCRPS sites were determined using a laboratory incubation assay. Three soil samples with a volume of 0.2 m × 0.1 m × 0.2 m (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 and 60 % soil water holding capacity in 150 mL bottles. Carbon dioxide fluxes were measured daily during the first 10 days, at three-day intervals for the next three weeks and in 1–2 week intervals afterwards. The gas measurement period was from 5 min to 4 h depending on the CO_2 fluxes. For flux measurements, the jars were closed gas-tight and CO_2 headspace concentrations were measured with a non-dispersive infrared sensor (Premier, Dynament, UK) at 10 s intervals. CO_2 fluxes were calculated from concentration changes with time, consider-

BGD
12, 3647–3674, 2015

ing headspace volume, temperature and air pressure. The total cumulative emissions were obtained by integrating the measured daily fluxes, with daily fluxes of the observational intervals being estimated as the arithmetic means of neighbouring data.

Soil organic matter fractions before and after incubation were physically separated 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 achievement of clear rinsing water. The fraction > 53 µm was dried at 40 °C and weighed. This large fraction contained sand-size particles and stable aggregates (Heavy fraction), as well as particulate organic matter (Light fraction). Both 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 settling overnight prior to freezing. The light fraction 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 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 analyser (Multi N/C 3100 Anaytik Jena, Jena, Germany).

Root biomass was quantified at one of our paired sites (32.07° N, 110.43° E). The experiment consisted of 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 complete 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. The soil from the different soil depths was placed

BGD
12, 3647–3674, 2015

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. The cleaned root sample in different soil depth was transferred into small envelope and oven-dried at 75 °C for 24 h.

2.4 Statistical analyses

Shapiro–Wilk tests were applied to check for normal distribution. Non-parametric tests were applied if the data was not normally distributed. First, *t* test was used to test for significant differences between GCRPS and Paddy in soil texture (clay, silt and sand content), bulk density, pH and mineral nitrogen concentrations (Nmin) at the regional scale. All statistical analyses and calculations were performed using parametric (paired and two-tailed *t* test,) and non-parametric (Wilcoxon matched pairs rank sum test; two-tailed) tests to investigate differences between GCRPS and Paddy at the regional scale. Statistical analyses of root biomass was performed using the general linear model (GLM) procedure of the Statistics Analysis System (SAS, version 8.2).

3 Results

Average soil organic C stocks and concentrations were significantly higher in GCRPS than in Paddy for each soil depth interval except for the 0–20 cm depth (Fig. 1a and c). Similar to SOC stocks and concentrations, soil organic N stocks and concentrations also tended to be larger in GCRPS than for paddy fields over the 1 m soil profile. However, significant differences were only observed in the 20–40 cm depth interval (Fig. 1b and d). There were no detectable differences in soil texture (Fig. 2a–c), pH or mineral N content (Fig. 2e and f) between GCRPS and Paddy for each soil depth interval. Soil bulk density (Fig. 2d) tended to be lower in GCRPS than in Paddy over the 1 m soil profile, although significant differences were only found in 20–40 cm depth.

The average C and N assimilation of aboveground biomass for GCRPS were significantly higher than for Paddy at maturity stage (Fig. 3). Root biomass was significantly

BGD
12, 3647–3674, 2015

affected by production system, but was not affected by N fertilizer rates or by the interaction of system and nitrogen fertilization. Pooled over the two N fertilizer rates, the root biomass at the maximum tillering stage was significantly greater in GCRPS than in Paddy for all soil layers down to 40 cm depth (Fig. 4).

The average soil δ^{15}N signatures were significantly lower in GCRPS than in Paddy for each depth interval (Fig. 5a; $P < 0.0001$, < 0.0001, $= 0.0002$, $= 0.0289$ for 0–20, 20–40, 40–60 and 70–90 cm). Meanwhile, the average δ^{15}N signature in plant leaves was also lower ($P < 0.0001$) in GCRPS compared with in Paddy at the maximum tillering stage (Fig. 5b). Ln-transformed soil N concentrations were inversely correlated with corresponding δ^{15}N values for either GCRPS or Paddy (Fig. 6).

Over the 200 day incubation period, there were no differences between GCRPS and Paddy systems in average potential C mineralization rates. In contrast, Paddy systems showed higher cumulative C loss rates compared with in GCRPS over the incubation period for the entire dataset (Fig. 7).

For the GCRPS, the SOC contents of the various fractions were similar before and after the incubation experiment (Fig. 8). However for the Paddy treatment, the amount of SOC in the heavy fraction was significantly lower after incubation compared to before incubation; although no differences were found in fractions of s + c, LF and DOC before and after the incubation (Fig. 8).

4 Discussion

The amount of organic C stored in soil is a fine balance between C inputs and decomposition processes (Jenny, 1941; Amundson, 2001; Saiz et al., 2012). It has been hypothesized that an absence of permanently anaerobic conditions and increased soil temperatures for GCRPS would result in either no change or increased SOC losses due to enhanced microbial decomposition (Pan et al., 2003, 2010; Qu et al., 2012). Two earlier studies showed trends towards lower SOC and total N stocks in fields using the plastic film-based GCRPS technique. However these previous studies only investigated

BGD
12, 3647–3674, 2015

the topsoil above the hardpan at a single study site (Li et al., 2007; Fan et al., 2012; Qu et al., 2012). By contrast, the large regional dataset presented here has been obtained by sampling cultivated fields at paired sites (i.e. both sites experience comparable soil and environmental conditions, Figs. 2 and S1 and Table S1) down to 1 m depth. Our results show that adoption of GCRPS has a positive effect on SOC storage (Fig. 1a) and concentrations (Fig. 1c) compared to the traditional Paddy cultivation system. 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 impact the amount and quality of organic matter above the hardpan, while the accumulation and stabilisation of subsoil organic matter in these agricultural systems derives mainly from dissolved organic matter leached from the plough layer (Tanji et al., 2003). In our study we observed significantly larger aboveground biomass and grain yields for GCRPS compared to traditional Paddy systems (Liu et al., 2013, 2014) (Fig. 3). Furthermore, root biomass was found to be significantly larger under GCRPS cultivation in all soil layers down to 40 cm depth (Fig. 4). This shows that plants growing in GCRPS have a more dynamic root system capable of acquiring soil nutrients in soil layers down to 40 cm depth. Recent literature has confirmed that rice cultivation under variable soil water regimes such as GCRPS result both in higher root biomass (Thakur et al., 2011; Uga et al., 2013), and in more rhizodeposits (Tian et al., 2013) compared to the flooded Paddy system. Also, the fluctuating soil water content inherent to GCRPS, which varies between 80–90 % water holding capacity (WHC), limits the accessibility of some micronutrients (i.e. Mn, Fe) as they become oxidised to forms that cannot be directly assimilated by the plant (Tao et al., 2007; Kreye et al., 2009). On the other hand, GCRPS promotes increased soil NO_3^- concentrations thus leading to a more balanced plant N nutrition (NO_3^- and NH_4^+), which is beneficial for the growth of the crop (Nacry et al., 2013). Therefore, the rice plants in GCRPS need to develop stronger root systems capable of access-

BGD
12, 3647–3674, 2015

ing deeper soil layers to obtain a balanced micro-nutrient supply, while avoiding iron toxicity effects (Bencjiser et al., 1984). Even if just a few fine roots penetrate the hardpan they may represent a large difference in SOC storage as root channels may further promote percolation of organic compounds into the subsoil. The strong anaerobiosis and stabilisation conditions prevailing at depth will likely promote OM accumulation below the hardpan; as was found in our study (Fig. 1).

b. *Greater physical protection of soil organic matter against microbial degradation.* We conducted soil incubations under controlled environmental conditions across all field sites to test the hypothesis that, in contrast to Paddy systems, the consistently high soil moisture conditions and high soil temperatures characteristic of GCRPS might increase mineralization and drive net losses of SOM (Farooq et al., 2009). Our results showed no difference in mineralization potentials between soils from the GCRPS and Paddy systems for all measuring dates over a 200 day incubation. On the contrary, soils from paddy fields showed higher cumulative C loss rates over the incubation period (Fig. 7). This indicated that SOM in fields managed under GCRPS is more effectively preserved than in traditional Paddy systems. Such stabilizing mechanisms may be conferred because of the higher OM inputs known to promote stable macro and mesoaggregates (Six et al., 2004) (Fig. 8), in addition to the physicochemical protection offered by clay minerals (Koegel-Knabner et al., 2010; Saiz et al., 2012). 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 stabilisation of organic matter in Paddy soils (Koegel-Knabner et al., 2010).

Similar to SOC stocks and contents, soil organic N stocks and contents were larger in GCRPS than for paddy fields over the 1 m soil profile. However, significant differences were only observed in the 20–40 cm depth interval (Fig. 1b and d). In addition,

BGD
12, 3647–3674, 2015

we observed δ^{15}N enrichment in paddy soils for all soil depths (Fig. 5a), which was also reflected in the plant biomass (Fig. 5b). 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), as well as (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, only 11 out of 98 sites received manure, (δ^{15}N > 10 ‰). Most crucially, N fertilization rates were comparable for both management systems (GCRPS: approx. 150 kg N ha^{-1}; Paddy: approx. 180 kg N ha^{-1}). Therefore, kinetic isotope fractionation processes in the soil rather than mixing of different N sources with distinct δ^{15}N signatures likely account for the observed differences in soil δ^{15}N. This is confirmed by the observation that ln-transformed soil N concentrations were inversely correlated with the δ^{15}N values (Fig. 6).

The largest fractionation factors are consistently reported for gaseous N losses (Bedard-Haughn et al., 2003; Robinson, 2001) so that changes in N_2, N_2O, NO and NH_3 losses may 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 mineral N cycling and associated denitrification losses as significant factors explaining lower δ^{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,

BGD
12, 3647–3674, 2015

2010) or manure deposits (Webb et al., 2013) greatly reduces NH_3 loss. Therefore, we expect that the observed greater soil N stocks in GCRPS fields were associated with decreased NH_3 volatilization.

5 Conclusion

We demonstrate for the first time that across a wide range of spatially representative paired sites under real farming conditions GCRPS significantly increased soil organic C and N stocks and concentrations at a regional scale under varying edaphic conditions. These indicate that GCRPS is a stable, sustainable and environmentally sound technique that can maintain key soil functions while increasing rice yields and expanding the cultivation of a valuable crop into regions where it has been hampered by low temperatures at the beginning of the growing season and/or a lack of irrigation water. However, the use of plastic sheets as cover material remains an obstacle, since plastic residues often remain in the field and pollute the environment. Biologically degradable films maybe 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.

The Supplement related to this article is available online at doi:10.5194/bgd-12-3647-2015-supplement.

Author contributions. M. Liu and M. Dannenmann contributed equally to this work. S. Lin and K. Butterbach-Bahl designed the experiments. M. Liu, S. Lin, M. Dannenmann, S. Sippel, Z. Yao and K. Butterbach-Bahl conducted the regional field sampling. M. Liu performed the lab analysis and statistical analysis. G. Yan and G. Saiz performed the incubation and fractionation experiment. Y. Tao and Y. Zhang carried out the field experiment and charged on the root biomass. M. Liu, S. Lin, M. Dannenmann, G. Saiz, K. Butterbach-Bahl and D. Pelster wrote the manuscript. All authors commented and revised the manuscript.

BGD
12, 3647–3674, 2015

Acknowledgements. This work was supported by the National Natural Science Foundation of China (NSFC 41371286, 51139006), and especially by the Sino-German Centre for Science Promotion (GZ667). KBB and DP were partly funded by the Climate Change Agriculture and Food Security (CCAFS) program of CGIAR institutes. We would like to thank the Agriculture Department of Shiyan for providing working facilities and organisation of soil and plant sampling.

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BGD
12, 3647–3674, 2015

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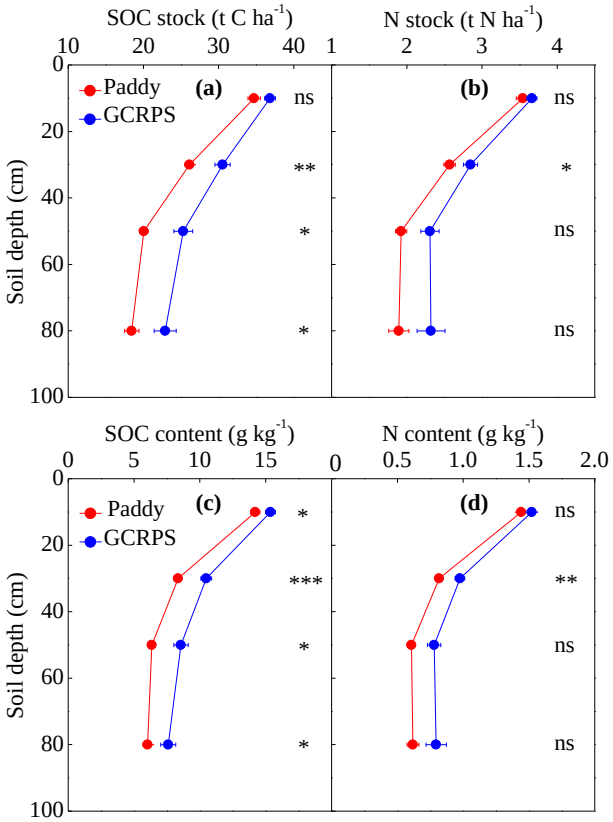

Figure 1. *Stocks and concentrations of soil organic carbon and total nitrogen in traditional Paddy and GCRPS at different soil depths.* Data presented are the mean values pooled over 49 paired sites (for 0–20 and 20–40 cm, n = 147; 40–60 cm, n = 108; 70–90 cm, n = 63). Bars indicate the standard error of the means. ***, **, * Significant at 0.001, 0.01, 0.05 probability level respectively; ns – not significant.

BGD
12, 3647–3674, 2015

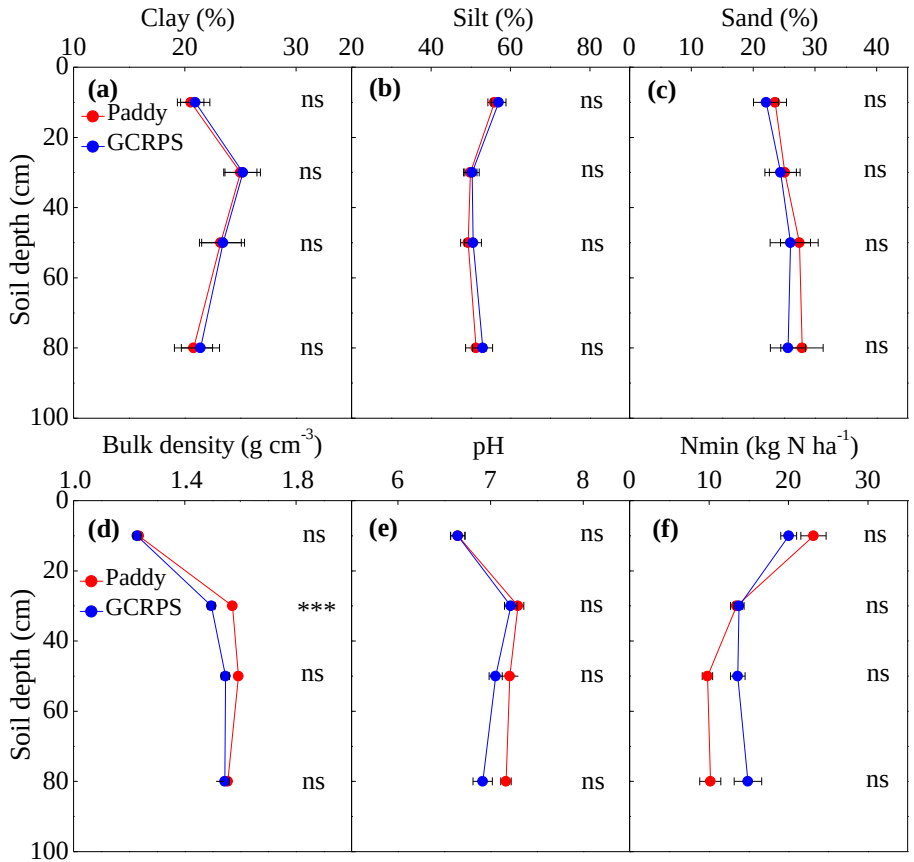

Figure 2. *Average soil clay, silt and sand content* (for 0–20 and 20–40 cm, n = 49; 40–60 cm, n = 36; 70–90 cm, n = 21), *soil bulk density, pH and mineral nitrogen concentrations* (N_{min}; for 0–20 and 20–40 cm, n = 147; 40–60 cm, n = 108; 70–90 cm, n = 63) *at different soil depths.* Errors bars indicate s.e.m. *** Significant at 0.001 probability level respectively; ns – not significant.

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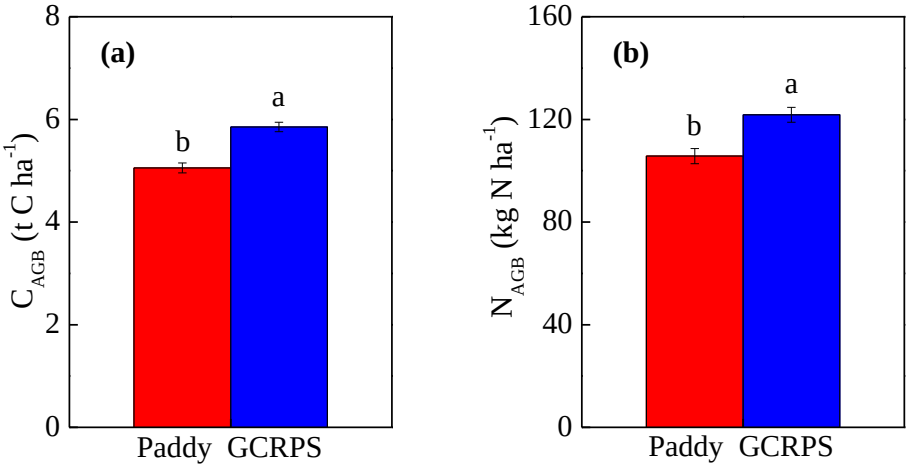

Figure 3. *Carbon* (C_{AGB}) *and nitrogen* (N_{AGB}) *assimilated in aboveground biomass at the maturity stage* (n = 108). Data presented are the means pooled over 36 paired sites (these represent all the sites where rice was grown in 2011) with three replicates at each site. Errors bars indicate s.e.m. Bars labeled with different lowercase letters indicate statistically significant differences ($P < 0.05$) between Paddy and GCRPS. For further details see Liu et al. (2013).

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12, 3647–3674, 2015

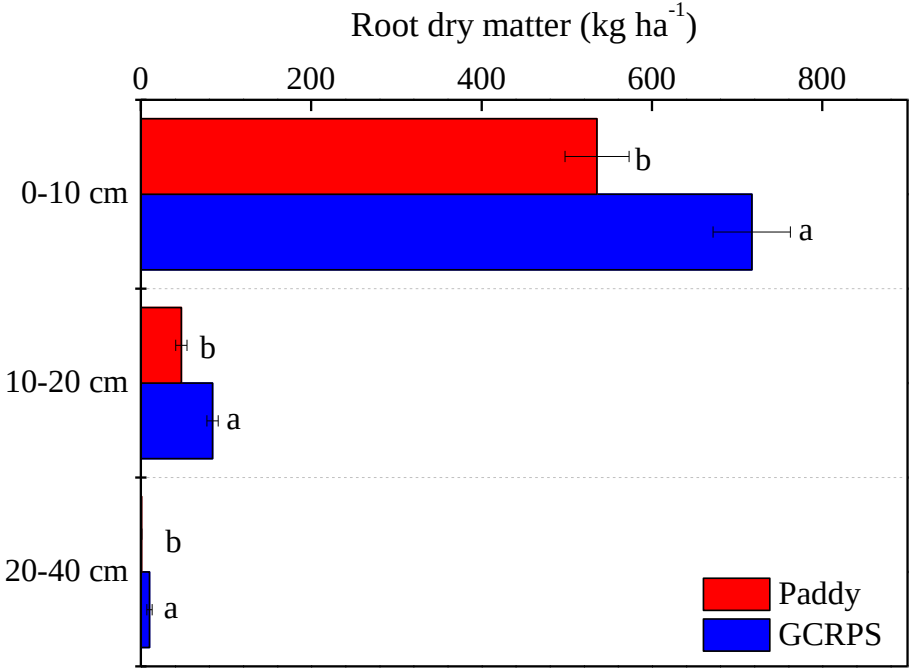

Figure 4. *Root dry matter at maximum tillering stage for different soil depths in Paddy and GCRPS. n* = 18. Error bars denote s.e.m. Bars labelled with different lowercase letters indicate differences ($P < 0.05$) between Paddy and GCRPS.

BGD
12, 3647–3674, 2015

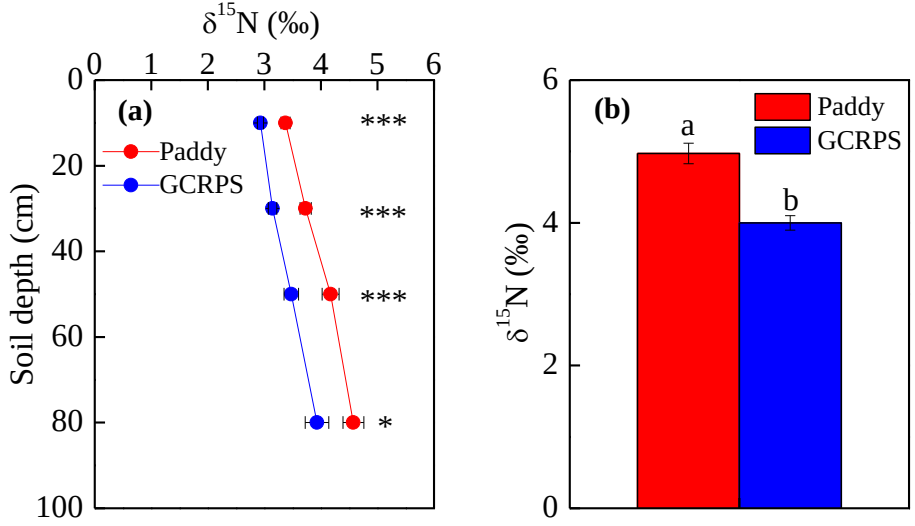

Figure 5. (a) *Soil δ^{15}N isotopic signature in traditional Paddy and GCRPS at different soil depths.* Data presented are the mean values pooled over 49 paired sites (for 0–20 and 20–40 cm, n = 147; 40–60 cm, n = 108; 70–90 cm, n = 63). **(b)** *δ^{15}N signature in plant leaves at the maximum tillering 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 = 108. Errors bars indicate the s.e.m. ***, **, * Significant at 0.001, 0.01, 0.05 probability level respectively; ns – not significant. Bars labelled with different lowercase letters indicate differences ($P < 0.05$) between Paddy and GCRPS.

BGD
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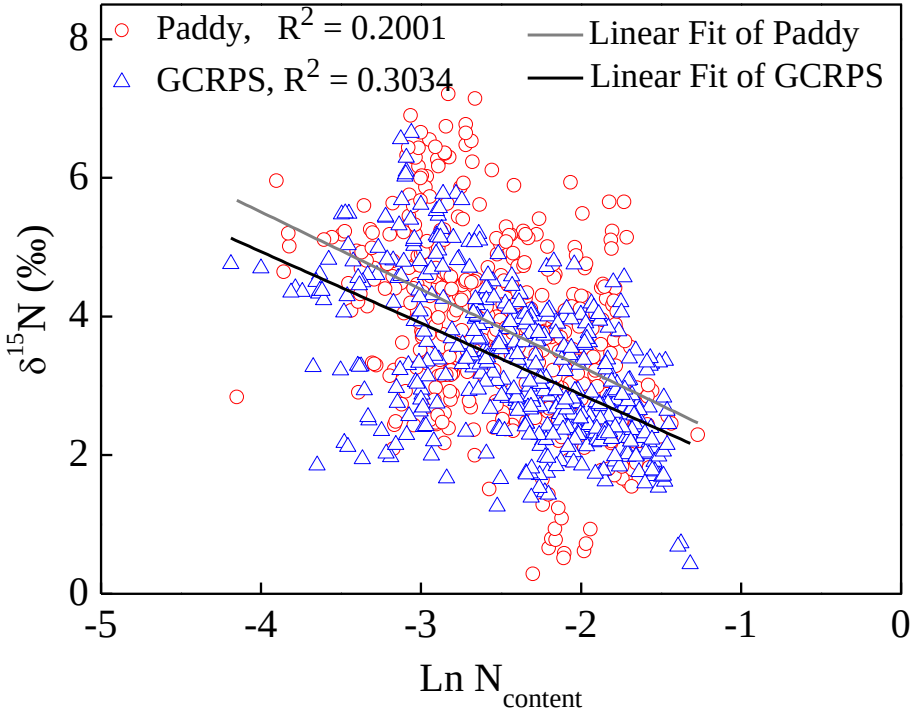

Figure 6. *Correlation of* δ^{15}N *with Ln transformed soil total nitrogen content up to* 1 m. Data presented are all the individual samples measured across the 49 paired sites, which consist of three replicates for each site (n = 465).

BGD
12, 3647–3674, 2015

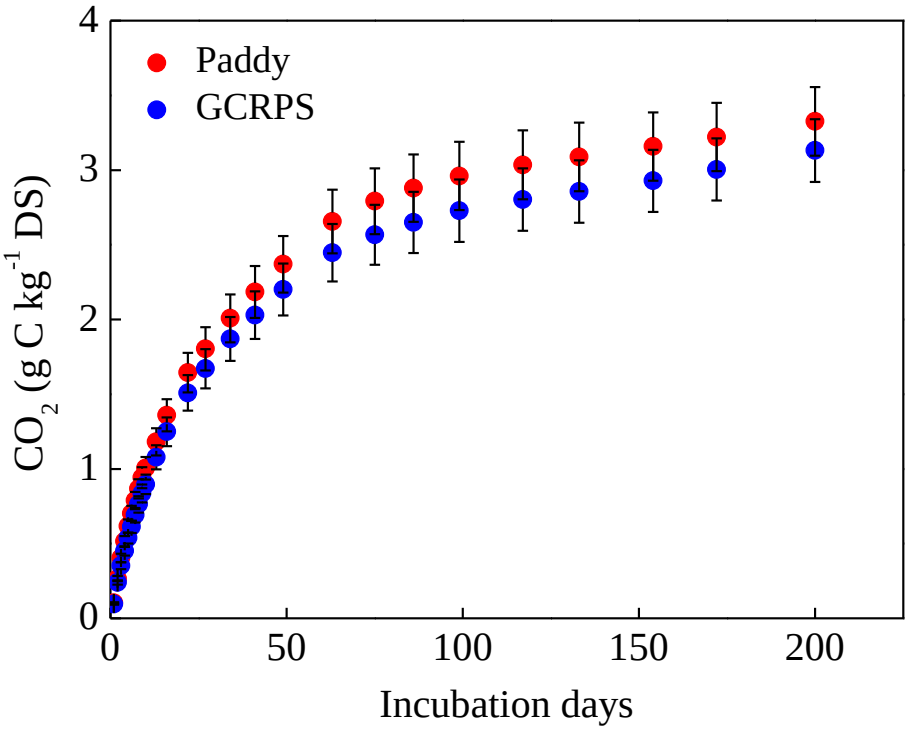

Figure 7. *Differences in cumulative organic carbon mineralization during a 200 day incubation period of top soils* (0–20 cm) *collected from either Paddy or GCRPS grown rice fields.* Data presented are the mean values pooled over 49 paired sites. Error bars indicate s.e.m. GCRPS and Paddy showed no significant differences for individual incubation times.

BGD
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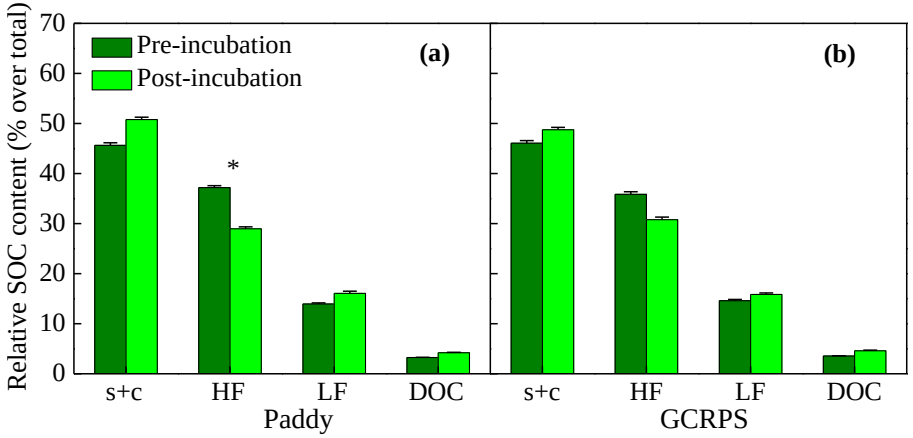

Figure 8. *Relative SOC distribution (% of total) of topsoils* (0–20 cm depth) *from either Paddy or GCRPS grown rice fields for the different physically separated fractions before and after a 200 day incubation.* $s + c$ = fraction < 53 µm, HF/LF = heavy/light fraction > 53 µm, DOC = dissolved organic carbon < 0.45 µm. GCRPS (n = 18) and Paddy (n = 18) (random selection of 18 out of 49 paired sites). Error bars denote s.e.m. The asterisk indicates significant differences between pre and post incubation (P < 0.05).

BGD
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