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Soil carbon and nitrogen mineralization dynamics following incorporation and surface application of rice and wheat residues

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Abstract

Understanding of crop residue mineralization is imperative for crop residue management in crop production. C and N mineralization dynamics of rice and wheat residues under surface applied and soil incorporated conditions were evaluated in an incubation experiment. Both rice and wheat residues were incorporated and surface applied. Soil moisture was maintained at 18% w/w (≈ – 15 kPa) during course of study. Periodic determinations on CO_2*–C and N mineralized were performed over a period of 120 days. The highest peaks for* CO_2*–C occurred during the first week of the incubation period. Significantly higher emission of* CO_2*–C occurred from rice and wheat incorporation treatments (50%) followed by surface application treatments (19%) as compared to control soil. Variations between rice and wheat residue either incorporated or surface applied were non-significant. Both rice and wheat residues either incorporated or surface applied immobilized soil mineral N. Peak for N immobilization in the incorporated treatments was on day 15 and then started mineralization while surface applied wheat and rice residue decreased soil mineral nitrogen gradually and continuously up to 75th day of incubation. Incorporated residues increased soil organic carbon and soil aggregate stability significantly by 18% and 55% over control respectively. This study indicated that crop residues incorporated into the soil have higher decomposition rate with a quicker mineral N release, more organic matter build up and soil structure improvement than retaining crop residues at the soil surface.*

Keywords: C mineralization, N mineralization, Rice and Wheat residues, crop residues application methods

Introduction

Crop residues are considered a vital natural resource for conserving and sustaining soil productivity. Addition of crop residue to soil is a useful tool in maintaining and increasing amounts of soil organic matter (Nortcliff and Amlinger, 2001). Therefore, the soils have significant capacity for C storage and to mitigate atmospheric CO_2 (Nieder and Benbi, 2008). Upon mineralization, crop residues also supply essential plant nutrients (Walters *et al.*, 1992). So, recycling of crop residues is suggested as a potential means of sustaining soil fertility and productivity over the long-term (Rasmussen and Parton, 1994; Carter, 2002; Singh and Rengel, 2007). Additionally, residue incorporation can improve physical and biological conditions of the soil and prevent soil degradation (Nyborg *et al.*, 1995).

Crop residues are completely removed from field and used for cooking food and feeding the animals. But recently, with the advent of mechanized harvesting in rice-wheat cropping system, farmers have been burning in situ large quantities of crop residues left in the field. As crop residues interfere with tillage and seeding operations for the next crop, farmers often prefer to burn the residue in situ, causing losses of soil organic matter (SOM) and nutrients, increasing C emissions, causing intense air pollution, and reducing soil microbial activity (Biederbeck et al., 1980; Rasmussen et al., 1980; Andreae, 1991; Nguyen et al., 1994; Kumar and Goh, 2000). To avoid these problems, recycling of rice and wheat residues with proper management has become important.

The management of crop residues is a key component of sustainable cropping systems and it has received much interest in recent years as a means of increasing soil organic matter and nutrient supplying capacity, reducing the ill effects of residue burning. For recycling crop residues, in situ incorporation and mulching with reduced or no tillage are the major residue management options. In the Rice-Wheat system of Pakistan, reduced and zero tillage allows farmers to establish a wheat crop almost immediately after rice harvest, thereby improving yields and input use efficiency whereas Direct Seeded Rice is used to overcome the ill effects of puddling on the ensuing wheat crop. Ortega et al. (2002) reported that the distribution of crop residue on the soil surface and incorporated residue into the surface soil changes dramatically with the initiation of no-till in the

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agroecosystems. Changes in these conditions should affect soil C and N dynamics (Ambus and Jensen 2001). Because the management of crop residues in the conservation tillage has crucial effects on soil chemical, biological, and physical properties and subsequent plant growth (Kumar and Goh 2003), a better knowledge about the crop residue decomposition and N mineralization (immobilization) dynamics of residue C and N is essential to quantify the potential benefits of changes in tillage practices and residue management on soil quality and crop production.

Soil microenvironments for biological and chemical processes differ in surface placed than in incorporated residues thereby influencing the nature and extent of organic matter dynamics and nutrient cycling (Beare, 1997; Cookson et al., 1998). Although the effects of placement on decomposition of different residues other than rice are known, information is lacking in the rice–wheat system, one of the world's most important cropping system. There is a need to study decomposition and nutrient dynamics in rice–wheat soils. This information would help in developing accurate composition of integrated nutrient management. Therefore, an incubation study was carried out to (1) predict decomposition and release of mineral N from rice and wheat residues; and (2) analyze the effects of placement on residue decomposition and mineral N dynamics.

Materials and Methods

Soil characteristics and crop residues

The soil used for this experiment was collected manually, using a shovel to a depth of 15 cm, from the Rice-Wheat area of central Punjab, Pakistan. Soil belonged to Gujranwala soil series (moderately well drained, non-calcareous, silty clay loam, hyperthermic Udic Haplustalfs) which was located with the help of Soil Survey Report, 1965, near Sadhoke, 5 km south east of GT road, Kamonke, district Gujranwala. The collected soil was brought to Soil-Plant Head House, LRRI, NARC. The soil was spread on plastic sheets, visible crop residue and pebbles were removed with hand. Soil was air dried and sieved through a 2 mm sieve. The soil was silty clay loam in texture having 8.2 pH, 0.15 dS m^{-1} EC, 20 g kg^{-1} $CaCO_3$, 2.3 g kg^{-1} organic C, 8.2 mg kg^{-1} mineral N, 2.8 mg kg^{-1} ABDTPA extractable P and 125 mg kg^{-1} K. Rice and wheat residues collected from the Rice-Wheat area at maturity, were also ground (<2 mm) and analyzed for organic C by dry combustion (Nelson and Sommers, 1982) and total N (Jackson, 1982). Organic C in rice and wheat residue was 50.21 and 53.84 % respectively whereas total N was 0.73 and 0.46 % respectively. The C/N ratio of rice residue was 69 while that of wheat was 116.

Prepared soil was placed on plastic sheet and moistened to 18% w/w (≈ −15 kPa) by sprinkling distilled water followed by gentle mixing. Soil water retention capacity at ≈ −15 kPa was determined by filter paper method (Deka *et al.*, 1996). A uniform dose of fertilizer (60 kg N ha^{-1}) was also applied to the soil by dissolving urea in water before sprinkling in order to allow decomposition without N limitation. The moistened soil was sealed in plastic bags and allowed to cure for 72 hours in a dark cold room to ensure uniform distribution of moisture throughput the soil and attain moisture equilibrium.

Wheat and rice whole plant residues were oven dried at 70°C and cut to < 2 mm long pieces. Two separate sets, one for CO_2 release and another for mineral nitrogen release were established. In total there were five treatments namely, Control soil (CS); soil + wheat residue surface applied (WRS); soil + wheat residue incorporated (WRI); soil + rice residue surface applied (RRS) and soil + rice residue incorporated (RRI). In each case residues @ 4.5 g kg^{-1} soil was either thoroughly mixed or spread uniformly on top of the moistened soil equivalent to 200 g of oven dry and incubated at room temperature (25ºC) for 120 days. A complete randomized design (CRD) with four replicates was used in this experiment.

Carbon mineralization

Soil samples were placed in air tight 1 L plastic jars along with a vial containing 10 ml of 1 M NaOH to trap the evolved CO_2 and a vial of water to maintain humidity. An absolute control treatment (empty jar) was also maintained as blank. Soils were incubated at 25 ºC and alkali traps were changed at 1, 3, 5, 10, 15, 20, 30, 45, 60, 75, 90, 105 and 120 d (days) after incubation began and CO_2 absorbed was analyzed by titration with 0.5 M HCl in the presence of $BaCl_2$ (Anderson, 1982). During and after titration, jars were left open for 3 h to fully replenish the jars with oxygen. The soil moisture content of the soil residue mixture was monitored throughout the study period by weighing and maintained by adding distilled water as needed periodically. At end of the experiment the soil in each jar was analyzed for soil organic carbon (Nelson and Sommers, 1982) and aggregate stability (Kemper and Rosenau, 1986). Soil stable aggregates (%) > 250 µm (macro-aggregates) were determined by using Wet Sieving Apparatus made by Eijkelkamp Agrisearch Equipment, the Netherlands.

N mineralization

The wheat and rice residue and the soil were treated and incubated in the same fashion as described for C mineralization. For mineral nitrogen (NH_4−N + NO_3−N) measurements, 200 g equivalent oven dry soil was taken in

1/2 L plastic jars (Length = 10 cm; Diameter = 8 cm), was incubated at room temperature (25ºC). On day 0, 15, 30, 45, 60, 75, 90, 105 and 120 after incubation began jars were removed destructively from the experimental setup and about 20g of soil from each removed jar was prepared and analyzed for mineral N determination. At each time samples so collected were air dried, sieved through 1 mm sieve and analyzed for mineral N (Keeney and Nelson, 1982).

Statistical analysis

Collected data were subjected to analysis of variance (ANOVA) for Completely Randomized Design (CRD) (Gomez and Gomez, 1984). Least significant differences at $p \leq 0.05$ was used to separate the means. At each sampling time means and standard errors were also computed for making comparisons.

Results and Discussion

CO_2 flux

There was a very rapid CO_2 emission rate in all treatments particularly at the onset of the experiment. The highest emission occurred within first 6 days of the incubation which then decreased gradually and levelled off until became linear from 30 day onward (Figure 1). The emission was greater in residue treated soil than in soil alone (control) treatment. Similar results have been observed by Mishra et al. (2001), Khalil et al. (2005), Kachroo et al. (2006) and Muhammad et al (2011). They observed highest peaks for CO_2–C release during the first week of the incubation periods. Krieft et al. (1987) and Curtin et al. (1998) attributed this highest peaks for CO_2–C release during the first week of the incubation period to the easily decomposable organic compounds occurred in crop residues during this time. The easily decomposable organic C release induced faster microbial growth in initial incubation period and decreased in later periods may be attributed to the exhaustion of those substances. While Martens (2000) and Stevenson (1986) reported that the high CO_2 release during the initial incubation period was due to the easily decomposable components, carbohydrates and amino acid contents, in the crop residues. In the beginning of the incubation period, treatments showed significant variations, these differences between treatments were small by the day 30 of the incubation. The highest peaks for the CO_2–C flux from the control soil was at day 2, whereas for crop residue treatments, both surface applied and incorporated, these were at day 6 of the incubation period which was due to the availability of more easily decomposable C in the residue treatments. The fluxes decreased thereafter in all treatments, but still remained higher in the crop residue treatments.

Total CO_2-C emission over 120 days incubation period also showed significant (p = 0.0000) variation between treatments (Figure 2). Both incorporation and surface application of rice and wheat residues treatments (RRI and WRI) evolved more CO_2–C than control soil. Crop residue incorporation treatments emitted significantly higher CO_2–C than the surface application treatments and control soil

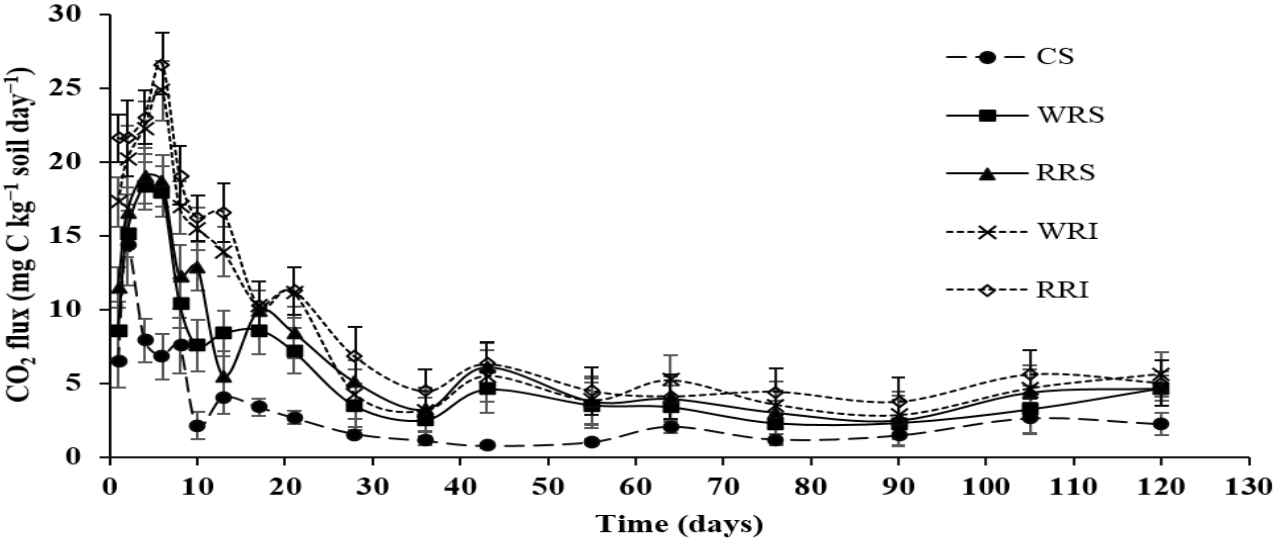

Figure 1: CO_2–C flux from rice and wheat residues under different crop residue applications to soil. Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated. Vertical bars represents standard error of means (n=4)

whereas the differences between control soil and surface application treatments were non-significant. Rice and wheat residues incorporation treatments evolved 50% while their surface application evolved 19% more CO_2–C over control soil (CS). Similar results were also reported by Henriksen and Breland (2002), Abiven and Recous (2007) and Coppens *et al.* (2007) that soil amended with crop residue either surface applied, heterogeneously layered or uniformly incorporated in to the soil release more CO_2–C as compared to un-amended soil.

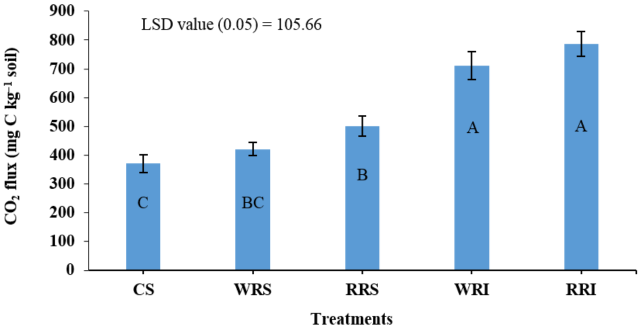

Figure 2: Total CO_2 flux from rice and wheat residue under different crop residue applications to soil. Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated. Vertical bars represents standard error of means (n=4). Treatments followed by different letters are significantly different at p = 0.05

Rice and wheat residue incorporation treatments (RRI and WRI) evolved 38% more CO_2–C than the surface application treatments (RRS and WRS). Beare *et al.* (2002), Ghidey and Alberts (1993) and Varco *et al.* (1993) observed that decomposition rates for many different residue types had consistently been 2–4 times faster in buried than in surface-placed. Irrespective of the incubation period, Jin *et al.* (2008) also observed the highest C mineralization in the incorporated winter wheat and peanut residues as compared to their surface application. Jin *et al.* (2008) also showed that winter wheat and peanut residues has slower decomposition when applied at the soil surface. Similarly Abiven and Recous (2007) also reported more C mineralization from paddy and wheat straw when incorporated into soil as compared to their mulching but these variations were non-significant. Faster decomposition with incorporated residues might be due to its close contact with soil, optimal moisture and temperature gradients and more availability of soil nutrients which in turn provide conducive environment for decomposition (Brown and Dickey, 1970; Douglas *et al.*, 1980; Schomberg *et al.*, 1994; Curtin *et al.*, 1998; Coppens *et al.*, 2007; Yadvinder-Singh et al. 2010). Rice residue treatments (RRI and RRS) released more CO_2–C than wheat residues treatments (WRI and WRS) under both manner of applications. But these differences were not significant. Rice residues with incorporation (RRI) released 10% more CO_2–C than wheat residue incorporation treatments (WRI) while in surface application treatments rice residues gave 16% higher CO_2–C flux than wheat residues. Higher release of CO_2-C from rice residue (C/N = 69) might be due to its narrower C/N ratio than wheat residues (C/N = 116). Our results agree with several studies which stated that plant residues with higher C/N ratios show slower decomposition rates (Kumar and Goh, 2000; Oliver *et al.*, 2002; Zhang *et al.*, 2008),

Nitrogen mineralization

Rice and wheat residue application (either incorporated or surface applied) considerably immobilized mineral N (Figure 3). Earlier studies have reported that residues with high C/N ratio exhibit immobilization (Van Kessel *et al.*, 2000; Qian and Schoenau, 2002; Nicolardot *et al.* 2001, and Muhammad et al., 2011). The immobilization is significant if the C/N ratio of plant residue is > 20–25 (Nicolardot *et al.* 2001). In our case both rice (C/N = 69) and wheat residues (C/N = 116) had greater C/N ratios than 20–25. Immobilization of mineral N may be due to the large demand for N by microorganisms proliferating rapidly in response to the availability of easily decomposable carbon compounds.

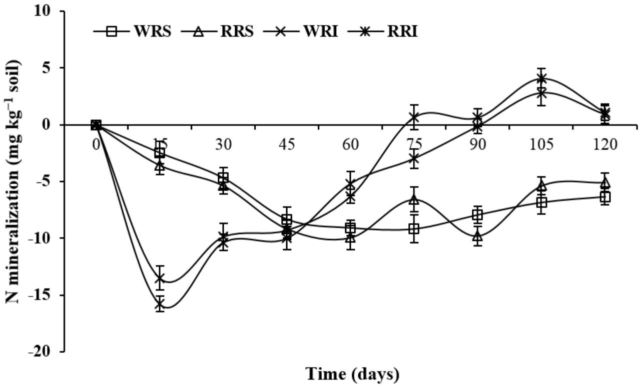

Figure 3: N mineralization from rice and wheat residues under different crop residue applications to soil. Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated. Vertical bars represents standard error of means (n=4)

Considerable differences in the pattern of N mineralization from incorporated and surface applied rice and wheat residue were observed (Fig. 3). In the case of surface applied rice and wheat residue treatments, immobilization of mineral N continued at a slower rate and did not contribute to mineral N up to the end of the experiment. In the first 15 days a net biological immobilization of mineral N was observed in rice and wheat residue incorporation treatments (RSI and WSI), however, a longer incubation period led to an increase in the mineral nitrogen for both crop residues. Similar results were found by Sirinavas *et al.* (2006) and Corbeels *et al.* (2000) who found the highest immobilization period of 12 days for incorporated residues whereas for Kachroo *et al.* (2006) this period was of 15 days. Rice and wheat residue incorporation treatments (RRI and WRI) immobilized 15.79 and 13.51 mg kg^{-1} mineral nitrogen at day 15. For crop residues incorporation treatments, after day 15, N mineralization started but with no net mineralization up to the day 75.

However, after day 75, some net N mineralization was observed and thus crop residues started to contribute mineral N to soil. Surface application of rice and wheat residues treatments (RRS and WRS) immobilized mineral N with a slower rate but immobilization prevailed over the whole incubation period. Highest immobilization of mineral N was found at day 75 for surface applied residues. After day 75, neither net immobilization nor mineralization was observed up to the end of the incubation period. Jin *et al.* (2008) also found a stronger immobilization for incorporation of winter wheat straw as compared to its surface application. This sharper immobilization and net mineralization in the incorporated residues might be due to the differences in the high contact of residue with soil, more moisture and nutrient availability (Brown and Dickey, 1970; Douglas *et al.*, 1980).

N mineralization of rice residues was found to be higher than the wheat residue but these differences were non-significant. This higher N mineralization of rice residues may be attributed to its lower C/N ratio than wheat residues. Whereas De Roy *et al.* (2011) found significantly higher mineralization from rice residue as compared to wheat residue.

Soil organic carbon (SOC) and Soil stable aggregates

Both rice and wheat residue incorporation treatments (RRI and WRI) significantly ($p = 0.0237$) increased SOC while its surface application did not affected SOC significantly (Figure 4). Residue incorporation treatments (RRI and WRI) increased SOC by 18% over control soil. Similarly Esther *et al.* (2013) observed that wheat straw amendment significantly increased total soil organic matter above the un-amended soil by 26 % for wheat straw incorporation treatments. High decomposition of incorporated residues also causes faster transformation of residues carbon into microbial components which may impact SOC by cycling C sooner into stable carbon pools that are protected (Moran et al., 2005).

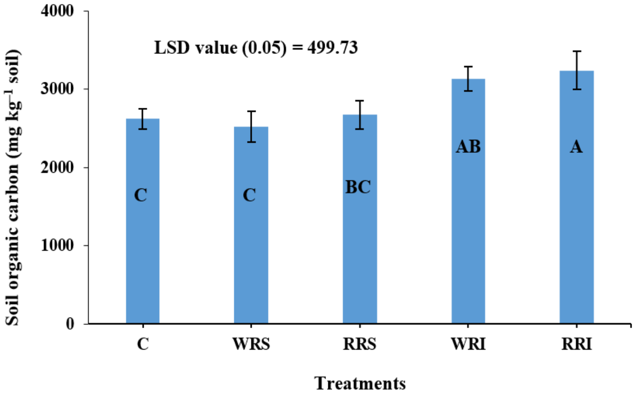

Figure 4: Soil organic carbon under rice and wheat residues with their different applications to soil. Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated. Vertical bars represent standard error of means (n=4). Treatments followed by different letters are significantly different at p = 0.05

Soil aggregate stability was also significantly ($P < 0.01$) increased only in crop residue incorporation treatments (RRI and WRI) (Figure 5). Crop residue incorporation treatments increased soil aggregate stability by 46% and 55% over surface application treatments and control soil respectively. Similar results were also reported by Martens (2000) who observed that addition of the seven plant residues increased soil aggregate stability for the soil at all incubation times when compared to the control (no residue added). Allison (1968) also reported that stabilization of soil aggregates is a function of the physical forming forces present in soils to form aggregates and the release of aggregating agents by soil microorganisms upon organic residue decomposition. Several other scientists also found that organic residues applied to soil improve structure by increasing soil aggregate stability (Waksman, 1936; Kononova, 1961; Sarkar and Rathore, 1992; Aggarwal *et al.*, 1995). High aggregate stability due to incorporated crop residue may be due to the high soil organic carbon content

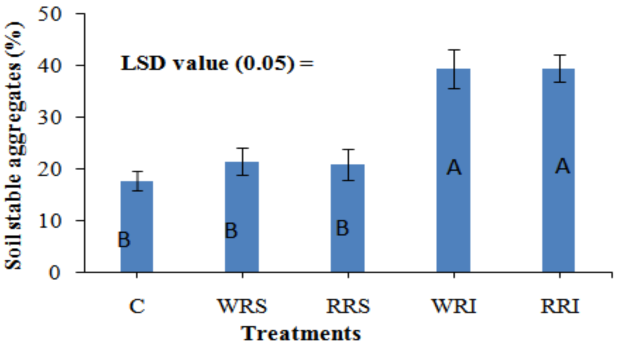

Figure 5: Soil aggregate stability under rice and wheat residues with their different applications to soil. Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated. Vertical bars represents standard error of means (n=4). Treatments followed by different letters are significantly different at p = 0.05

in those treatments which act as a cementing agent for aggregate formation and stabilization (Chaney and Swift, 1984). Therefore, a significant relation between SOC and soil stable aggregates was observed in this study (Figure 6) which showed that the increase in soil stable aggregates due to soil organic carbon was 52% (R^2 = 0.5149) which was statistically significant (p = 0.0003). Similar relation was also observed by Stengel *et al.* (1984) with a regression equation (12.75 + 11.75 SOC (%); R^2 = 0.61, $P < 0.001$).

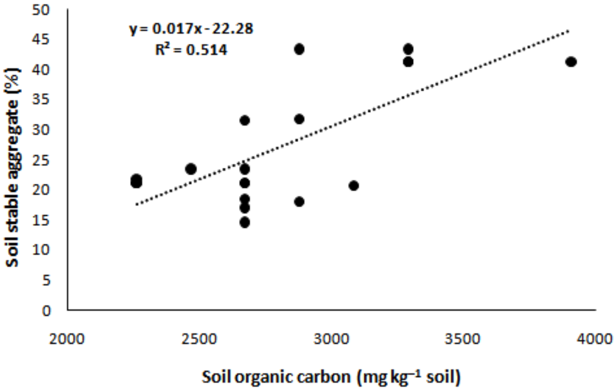

Figure 6: Regression analysis of soil organic carbon and soil aggregate stability

Conclusion

Mechanized harvesting in rice wheat cropping system leaves behind about 4–5 Mg ha^{-1} of crop residues which creates hindrance in seedbed preparation of succeeding crop. For a quick seedbed preparation, farmers burn these residues which creates soil health and environmental problems. Our observations showed that rice residue has faster C mineralization rates than wheat residues. Further the mineralization rates were faster when residues were incorporated into soil than surface applied. The residue incorporation significantly enhanced its decomposition and caused about 30 kg N ha^{-1} (15 mg N kg^{-1}) immobilization within 15 days whereas surface application immobilized about 19 kg N ha^{-1} (9.5 mg N kg^{-1}) in 75 days. In rice-wheat area of Pakistan, the time window between wheat harvesting and rice transplanting is about 60 days which provides enough time for crop residues to decompose and mineralize N. But the time window between rice harvesting and wheat sowing is about 20–25 days thus incorporation must be as early as possible just after rice harvesting and a starter dose of about 10–15 N kg ha^{-1} should also be applied in order to avoid N deficiency during germination and early growth. In the zero drill system crop residues can be left intact or used as mulch in the direct seeded system. In case of surface application of rice and wheat residues, the immobilization process is very slow and long which will not cause N deficiency with the application of recommended dose of N fertilizers.

Incorporated rice and wheat residues increased soil organic carbon by 18% while soil stable macro-aggregates by 50% over un-amended soil. Low organic matter and poor soil structure are one of the key reasons of yield stagnation and even decline in yield of rice-wheat system of Pakistan. Therefore, crop residue incorporation will enhance soil organic matter and will improve soil structure. It is important to underline that the laboratory conditions of the experiments are different from those under field conditions, where gradients in temperature, moisture and N are associated with residue location (Coppens et al. 2006).

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