Assessing soil carbon sequestration in upland rice systems using rice straw and mycorrhiza

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Abstract. Global warming has many negative impacts, such as droughts, floods, and crop failures. Agricultural cultivation activities can capture and produce CO₂. This study aims to assess the sequestration and release of carbon from the cultivation of upland rice with straw and mycorrhiza application. This field study used two factors (types of straw and levels of mycorrhiza) which were arranged in a Completely Randomized Block Design. The first factors were three types of straw (control, fresh and weathered), and the second factors were two levels of mycorrhiza. The results showed that application of straw and mycorrhiza significantly increased the C storage soil. Furthermore, the application of fresh and weathered straw incorporated with mycorrhiza increased C sequestration up to 24,449.81 kg Ha⁻¹ and 26,631.73 kg Ha⁻¹.

1. Introduction

Global warming caused by the increase of greenhouse gas (GHG) concentration in the atmosphere has received much attention from various circles because it can give negative impacts, such as drought, flood, and crop failure [1]. CO₂ is one of the greenhouse gases that have a big role in global warming so that the concentration in the atmosphere needs to be lowered by reducing the emission. Another way is also by removing and storing CO₂ in the soil [2], since it comes from a variety of land use and cultivation changes that contributes one-third of the GHG emissions in the atmosphere [3]. Besides, the improved of management in cultivation can also mitigate climate change and reduce emissions from agriculture and other sources and store them in both plant and soil biomass [4].

Carbon storage in soil is important to mitigate GHG, the quantity is influenced by several factors such as C input [5], and the management of plant residues [6]. Therefore, various management practices of organic materials will affect soil organic C sequestration. The results of the study show that the application of organic matter can maintain soil organic C, provide plant nutrients and have an impact on improving soil structure [7]. On the other hand, organic materials such as straw as a source of carbon dioxide are given to the soil because it will decompose and produce atmospheric CO₂ and simultaneously it also adds organic C to the soil [8].

Mycorrhiza application is another way of improving crop yields through its ability to increase nutrient uptake [9]. It also can overcome the stress of water shortages [10] and increase soil organic C.
as it produces glomalin containing C \([9][10]\) and \(\text{CO}_2\) from respiration \([11]\). Based on these conditions, it can be explained that management in cultivation will affect the loss and acquisition of organic C in the soil\([12]\). This study aims to assess the sequestration and release of carbon from the cultivation of upland rice in Alfisols with straw and mycorrhiza application.

2. Methods
This field research conducted on Alfisols, Karanganyar, Indonesia using two factors and four replications. This study used a Completely Randomized Block Design. The first factor was 3 types of straw, i.e. without straw (control), fresh straw and weathered straw. The second factor was 2 levels of mycorrhizal application (with and without mycorrhiza). The definition of fresh straw is original straw from harvesting and weathered straw is straw which left in dry for one season. Two types of straw were given by spreading and mixing it into each plot and then incubated for 4 weeks. Mycorrhiza was applied when planting. IR 64 (varieties were grown by local farmers) that has been seeded for 15 days was planted 1 seedling in each planting hole with spacing 25 x 25 cm in pot size (2 x 6 m). Plant maintenance was done in accordance with local farmers' habits.

Data for plant observation were taken 3 plants per plot. The samples were taken from the field research before and after the experiment. The observed variables included \(\text{CO}_2\) emissions with Closed Chamber, organic C from fresh and weathered straw, C roots, C plants, C grains and soil organic C. The observed data were analyzed using F-variance test at 5% level of probability, continued with Multiple Range Test (DMRT) test, and correlation test \([13]\).

Measurement of sequestration within a given time range referred to the balance of the amount of carbon entering and the amount of C out \([14]\). The sequestration C would occur if the amount of incoming C is greater than the outgoing C \([15]\). The incoming C was calculated from the root C left in the soil, the added straw C, and the soil C deposit. Meanwhile, the outgoing C in the form of \(\text{CO}_2\) and C emissions in grain was calculated from the Stages of carbon storage measurement as it is called as the concentration of C.

3. Results and Discussion
Alfisols used in this study has a relatively low fertility. This can be seen from the total organic C content (COT) which was very low (Table 1). Similarly, the nutrient content of N, P, K and Ca were also very low. This is allegedly related to farmers' habits that do not return plant residue to the soil so that there was no organic fertilizer applied in the soil.

| Soil Characteristics                  | Value | Level   |
|---------------------------------------|-------|---------|
| pH \(\text{H}_2\text{O} (1:2.5)\)     | 5.93  | Acid    |
| C organic (%)                         | 0.95  | Very low|
| Organic matter (%)                   | 1.66  | Very low|
| Total Nitrogen (%)                   | 0.11  | Low     |
| C/N Ratio                             | 8.74  | Low     |
| \(\text{P}_{2}\text{O}_5\) Bray (ppm) | 6.90  | Low     |
| Exchangeable K (cmol\(\cdot\)kg\(^{-1}\)) | 0.31  | Low     |
| Exchangeable Ca (cmol\(\cdot\)kg\(^{-1}\)) | 3.24  | Low     |
| Exchangeable Mg (cmol\(\cdot\)kg\(^{-1}\)) | 2.95  | Moderate|
| Exchangeable Na (cmol\(\cdot\)kg\(^{-1}\)) | 0.77  | Moderate|
| Cation Exchange Capacity (cmol\(\cdot\)kg\(^{-1}\)) | 20.00 | Moderate|

The main problems in Alfisols are the low organic of C and nutrients and the limited supply of water. These conditions lead to low soil productivity of Alfisols. One way in improving the soil organic C is by giving organic materials such as straw \([8]\) since organic materials could improve the chemical, physical and biological properties in the soil \([16]\), the availability of plant nutrients, the
water holding capacity, the crop yields, and the lower of soil erosion that is also associated with an increase in total soil carbon (TSC) saving [17].

3.1. CO₂ emission

Mycorrhiza inoculation accompanied by fresh or weathered straw were significantly increased the CO₂ emissions (P < 0.05). Table 2 shows that application of fresh or weathered straw with or without mycorrhiza inoculation could increase the CO₂ emissions significantly. CO₂ emissions range from 3.2 to 4.77 kg Ha⁻¹Season⁻¹. It is lower than Reddy and Delaune [18] reported that CO₂ emissions per year of 4.4 and 6.5 kg of CO₂ per Ha from the supply of 0 and 8 tons Ha⁻¹ of wheat straw, respectively, but it is similar to Gomez and Gomez [15] that obtained CO₂ emissions of 3.8 and 5.3 kg Ha⁻¹. Some previous researchers have also reported higher CO₂ emissions per year. CO₂ emissions on maps measured with plants (including root respiration and decomposition of organic materials by microorganisms) are 5.38; 7.64 and 7.27 kg CO₂ Ha⁻¹ year⁻¹, respectively in 2003, 2004 and 2005 reported by Jacinthe et al. [19].

Table 2. The CO₂ emissions after application of fresh or weathered straw with or without mycorrhiza inoculation (kg Ha⁻¹ Season⁻¹).

| Straw              | Mycorrhiza inoculation | Average |
|--------------------|------------------------|---------|
|                    | Without                | With    |
| Without (control)  | 3.42⁺                 | 3.20⁺   | 3.32   |
| Fresh straw        | 4.77ᵇ                 | 4.54ᵇ   | 4.65   |
| Weathered straw    | 4.71ᵇ                 | 4.46ᵇ   | 4.58   |
| Average            | 4.30                   | 4.07    |

Values indicated by different letters within columns are significantly different at the 5% level by Duncan’s multiple range tests.

3.2. Soil organic carbon

Mycorrhiza inoculation accompanied by fresh or weathered straw were increased the total C organics. The direct effect of inoculation of mycorrhiza will improve soil structures and provide hyphae mycorrhiza development. The hyphae will be decomposed and formed to the soil organic carbon and produced C glomalin. The contribution of C from glomalin ranges by 27% from soil organic carbon [13]. The indirect effect of straw application will give a good condition for root development so the activity of mycorrhiza will be increasing. Moreover, the application of fresh and weathered straw without mycorrhiza increases soil organic C up to 13.3% compared with control. The result is same as with Zhijian et al. [20] that there is an increase in soil organic C as a result of giving straw to the soil.

Table 3. The soil organic carbon (%) after application of fresh or weathered straw with or without mycorrhiza inoculation

| Straw              | Mycorrhiza inoculation | Average |
|--------------------|------------------------|---------|
|                    | Without                | With    |
| Without (control)  | 0.98⁺                 | 1.10⁺   | 1.04   |
| Fresh straw        | 1.11ᵇ                 | 1.14ᵇ   | 1.13   |
| Weathered straw    | 1.11ᵇ                 | 1.20ᵇ   | 1.15   |
| Average            | 1.07                   | 1.15    |

Values indicated by different letters within columns are significantly different at the 5% level by Duncan’s multiple range tests.

Inoculation of mycorrhiza increased soil organic C by 12.24% compared with no mycorrhiza. This is due to mycorrhiza will increase photosynthesis, and photosynthesis (photosynthate) in host plants ranged from 27-68% of net primary productivity (NPP). The NPV will be transferred to mycorrhizal hyphae and approximately 1 – 2% of carbon will be allocated into hyphae of mycorrhiza [21], which is
one of the constituent components of soil organic C. Besides, mycorrhiza also produces enzymes that will destroy organic compounds such as protein, chitin, pectin, and others to component of soil organic C.

3.3. Carbon uptake by Oryza sativa

Application of straw parallel with inoculation of mycorrhiza were significantly affected the C uptake of grain ($p = 0.003$) and total C uptake ($p = 0.025$). C uptake of grain ranged from 112.20 to 151.34 kg Ha$^{-1}$. Total C uptake ($C_{\text{root}} + C_{\text{straw}} + C_{\text{grain}}$) from the straw application and mycorrhiza inoculation is varied with a range from around 425 to 570 kg Ha$^{-1}$ (Table 5).

The application of weathered straw with mycorrhiza inoculation shows the highest increase because it has C root, C straw, C grain, root weight, straw weight and grain weight which are higher than other treatments. The highest grain C uptake occurred in plots which were given weathered straw without mycorrhiza which was almost 30% of the total C uptake and the lowest was in without straw plots and with mycorrhiza inoculation nearly 25% of total C uptake (Table 5). The grain uptake of C in the plot with fresh and weathered straw were almost the same, about 28% of the total C uptake. In the without straw treatments, the lowest grain C uptake is about 25% of the total C uptake. Overall the application of straw shows a higher total C uptake than without straw.

3.4. C Sequestration

The carbon dynamics are divided into input and output. Carbon inputs consist of organic (straw) and residual of harvest; and carbon output consists of gaseous (CO$_2$), and harvest (straw and grain). C sequestration calculation is based on the balance between C input, output and soil organic C [15]. The variation of carbon dynamics will be affected to C sequestration in the soil.

**Table 4.** Carbon sequestration in Gogo Rice in Typic Hapludalf with the application of fresh or weathered straw with or without mycorrhiza inoculation

| Treatments | Root$^a$ | Straw$^a$ | Total$^a$ | Harvesting | Gaseous$^a$ | Total$^a$ | $\Delta C^a$ (kg Ha$^{-1}$) | Total Soil C$^b$ (kg Ha$^{-1}$) | C Seq$^{10}$ (kg Ha$^{-1}$) |
|------------|---------|---------|---------|------------|-----------|---------|----------------|----------------|-----------------|
| Without straw and mycorrhiza | 161.72  | 0.00    | 161.72  | 151.63     | 112.20    | 0.93    | 264.76        | -103.04        | 21240.88        |
| Without straw, with mycorrhiza | 100%$^{11}$  | 0%      | 100%    | 57.27%$^{12}$ | 42.38%    | 0.04%   | 100%          | 22788.68        | 22642.69$^a$   |
| Fresh straw, without mycorrhiza | 184.29  | 0.00    | 184.29  | 201.88     | 127.52    | 0.88    | 330.28        | -145.99        | 24272.01        |
| Fresh straw, with mycorrhiza   | 100%    | 0%      | 100%    | 61.12%     | 38.61%    | 0.03%   | 100%          | 170.69         | 24685.37$^a$   |
| Weathered straw, without mycorrhiza | 21.23% | 78.77%  | 100%    | 55.92%     | 43.62%    | 0.05%   | 100%          | 24048.55        | 24449.81$^a$   |
| Weathered straw, with mycorrhiza | 25.66% | 74.34%  | 100%    | 58.87%     | 41.22%    | 0.04%   | 100%          | 24327.83        | 24519.83$^a$   |
| Weathered straw, with mycorrhiza | 31.32% | 68.68%  | 100%    | 55.09%     | 44.48%    | 0.43%   | 100%          | 26422.58        | 26631.73$^a$   |

1 Root C x dry weight of root + Rice hump)  7. Sum of columns 4+5+6
2 Straw C x dry weight of straw application  8. Difference between C input and output (3-7)
3 Sum of columns 1 + 2  9. Soil C x BD x soil depth (20 cm) x area (1ha)
4 C of the Straw x dry weight of straw harvested  10. C seq = (3-7)$^a$ + $9$
5. Grain C x dry weight of grain  11 and 12 Italic numbers are a proportion between C input on C output (%)
6. CO$_2$ emission (12/44* emission CO$_2$)

Straw management has a big influence on the flow of C on upland rice, in all treatments. Around 55-61% C is lost from straw and transported in the harvest (Table 5). The return of straw will increase soil C with a range between 60-79% while the loss in the form of grain ranges from 38 - 43%. The
smallest loss of C in grain occurred at without straw and mycorrhiza. The biggest C loss occurred in weathered straw treatment with mycorrhiza. The losses C grain in inoculation of mycorrhiza was higher than without mycorrhiza, due to higher C and grain yield. The C input from the root is the largest input component in the plot without straw (100%), while in the plot with straw, the root C component provides a supply about 21-40% of the total input. The supply of root C from the plots with weathered straw is higher than the plot with fresh straw, due to the higher content of C and root weight in plots with weathered straw.

Loss of C in the form of CO$_2$ gas only ranged from 0.4 - 0.6% of the total loss. Table 5 shows that more than 80% C in the final balance comes from the total organic C soil. In the treatment without straw and mycorrhiza, there is C sequestration even though there is no return of straw. This is presumably derived from the root exudate and various other microorganisms as stated by Talbot et al. [22] that although there is no addition of mycorrhiza, it is suspected that there are other fungi that produced mucilages which is important in soil aggregation and C sequestration. This condition indicates a stabilization C organic by soil components and soil aggregate (<0.05 mm) [23]. Furthermore, C sequestration in control (without straw and mycorrhiza) is the lowest. In a cultivation system, if C input into the soil exceeds C output, it will occur C sequestration in the soil [25]. Jacinthe et al.[19] reported that the addition of carbon input such as wheat straw compost will give sequestration of C[18].

The application of straw in both fresh and weathered conditions were increased the total organic C of the soil, even though it is accompanied by CO$_2$ emissions. Furthermore, mycorrhiza inoculation were increased CO$_2$ emissions, total organic C and dry grain. The application of straw with mycorrhiza produces a positive C balance. Application of straw with mycorrhiza is an effective way to reduce carbon loss while increasing yield. The application of fresh straw with or without mycorrhiza shows high C stores, but it is not followed by high grain yields. On the other hand, the application of weathered straw with or without mycorrhizal inoculation causes a lower deposit of C but more grain yield is obtained. Nevertheless, there are no significant differences between the two straw conditions given. Therefore, in order to obtain C sequestration and high grain yield, the addition of straw to the soil is important, with or without mycorrhiza.

4. Conclusion
The application of straw in both fresh and weathered conditions were increased the total organic C of the soil. Then, application of fresh and weathered straw incorporated with mycorrhiza increased C sequestration up to 24,449.81 kg Ha$^{-1}$ and 26,631.73 kg Ha$^{-1}$, respectively. The application of fresh or weathered straw with inoculation of mycorrhiza on dryland needs to be continued for maintenance of Organic C in the soil and CO$_2$ mitigation.

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