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SHORT COMMUNICATION

Fine Roots Carbon Mineralization and Soil Carbon Stabilization Under Major Tree Species of the Semi-arid Region of India

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Abstract Below ground biomass is a major determinant of soil carbon (C) storage in semi-arid ecosystem. An extended laboratory incubation study for a period of 323 days was carried out to ascertain the decomposition kinetics of fine roots of major trees (*Jatropha curcas, Leucaena leucocephala, Acacia nilotica, Azadirachta indica* and *Prosopis juliflora*) and a grass species (*Cenchrus ciliaris*) in the semi-arid region of India with the hypothesis that species with a slower decomposition rate will increase stability of soil organic carbon and will have higher potential to rehabilitate degraded sites in terms of soil quality. The results were confirmed by analyzing bio-chemically stabilized carbon pool of soils under different species. Decay constant (k) for fine roots carbon ranged from 0.14 to 0.21 year^{-1} under different tree species and followed the order; *Acacia* > *Jatropha* > Grass- *C. ciliaris* > *Leucaena* > *Azadirachta* > *Prosopis.* Acid non-hydrolysable C (biochemically stabilized C pool) of soil was maximum in *P. juliflora* (1.84 g kg^{-1}) followed by *Azadirachta* (1.79 g kg^{-1}). Results emanating from the present investigation suggest that fine roots of *A. indica* have greater carbon stabilization potential than other species of the region.

Keywords Fine roots · Semi-arid · Tree species · Carbon mineralization · Bio-chemically stabilized carbon · Decay constant · Residue quality

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Introduction

The amount of carbon (C) stored in a soil is a function of the difference between C inputs, such as those from plant litter and roots, and C outputs, primarily through decomposition but also from the burning of organic material [1] and removal by erosion and leaching. The fine root system of forest plays a crucial role in the fluxes of energy and matter in the biosphere and carries out the essential function of soil resource acquisition [2]. Root decomposition is an often ignored, yet potentially important regulator of carbon and nutrient cycling [3]. The belowground inputs into tropical soils may be of great importance for maintaining the soil organic matter level because litter, in general, is rapidly mineralized to CO_2, whereas the root residues, which are in close contact with the mineral soil, have more chances to be stabilized by clay particles or sesqui-oxides [4].

The land restoration potential of different semi-arid tree species depends on leaf litterfall and fine root production and subsequently on the rate of decomposition. However, our knowledge about the decomposition kinetics of fine roots of tree species of the semi-arid region and their impact on soil carbon stabilization is poor. Measurement of

CO_2 production provides considerable insight into the functioning of soil microbial decomposition systems [5, 6] and is often used for characterizing decomposability of residues [6–8]. Furthermore, CO_2 evolved in laboratory experiment agrees well with residue decomposition rates measured in field experiments [8, 9].

Many of the important factors regulating the decomposition rates of aboveground litter are well known for forest ecosystems [10–12]. However, for fine roots, C mineralization dynamics and the proportion of C retained in soil are not well documented [13]. In semi-arid ecosystem, species with slower decomposition rate (recalcitrant) would be preferable as they sequester the nutrient and C for a longer duration. In this paper, we estimated long-term decomposition patterns of fine roots of different semi-arid tree species in extended laboratory incubation study and subsequently, we measured the stabilized C in soil under different tress species (block plantation) for validation of results obtained from laboratory incubation study. We hypothesized that species with slower decomposition rate will be better for stabilization of soil organic C since rapid decomposition may lead to losses of nutrients and soil organic matter due to excessive runoff and soil loss under the ravinous landform. Therefore, the present investigation was carried out with the objective to study the decomposition pattern of fine roots of semi-arid tree species with a view to screen the best species that could increase the biochemically stable C pool of soil.

Materials and Methods

Plant Materials and Chemical Analyses

Fine roots of five tree species (*Jatropha curcas, Leucaena leucocephala, Acacia nilotica, Azadirachta indica* and *Prosopis juliflora*) and a grass (*Cenchrus ciliaris*) were selected for the study. These are commonly found species of semi-arid region of India. The details of soil and trees species characteristics, fine root sampling technique, production and turnover of fine root data are given in a published paper of Jha and Mohapatra [14]. In brief, sequential coring was done to determine the fine root mass from the block plantation of each species for conducting laboratory incubation study. Roots were collected from the top 30 cm of soil depth using a core auger and the roots collected from each site were homogenised and separated into fine root (<2 mm) mass. The roots were washed carefully and dried at 50 °C and were used for incubation. Roots were separated from soil by soaking in water and then gently washing over sieves with mesh size of 5 and 0.5 mm [15]. Roots >2 mm were regarded as fine root in the present investigation.

Chemical Analysis of Fine Roots

Samples of roots collected were thoroughly mixed and dried at 50 °C, ground and passed through 20-mesh screen. Fine roots total carbon content was determined by chromic acid digestion method with external heating [16]. Total nitrogen (N) was determined by Kjeldahl method. For phosphorus (P), potassium (K), calcium (Ca) and sodium (Na), samples were pre-digested in HNO_3 and were finally digested in di-acid mixture (9:4 of HNO_3:$HClO_4$). Phosphorus content was determined by a colorimetric method and K, Ca and Na by a flame photometric method. Total polyphenols were determined by the Folin–Ciocalteau method [17] using gallic acid as standard.

Fine Root Decomposition Measurements

For this estimation, 0.5 g of fine roots (collected from block plantation of each tree species) was thorough mixed with 100 g of soil and placed in 500 ml conical flasks. The soil moisture was adjusted to 60 % of field capacity to simulate the average field moisture condition and incubation was carried out at room temperature of 25 ± 2 °C. A vial containing 5 ml of 2 M NaOH was placed inside the flask with help of thread and flasks were sealed (air-tight) with wax. Each treatment (unamended soil and soil mixed with fine roots) was replicated three times at each sampling date. Additionally, three flasks without soil and fine root were also taken, which were considered as blanks. The vials were taken out on 7, 15, 30, 60, 120, 240 and 323 days interval and titrated with 0.5 M HCl after addition of 1 ml of saturated $BaCl_2$ using phenolphthalein as visual indicator. The amount of CO_2–C evolved was calculated by using the formula;

$$\text{C}-\text{CO}_2 \text{ evolved } \left(\text{mg } 100 \text{ g}^{-1}\right) = (\text{A} - \text{B}) * \text{N} * 6,$$

where A and B are the volume of HCl consumed for titrating 5 ml of 2 M NaOH in control and amended soil and N is the normality of HCl. Decomposition is reported as a percentage of the original C remaining:

$$\text{Net C evolved} = \text{C amended} - \text{C control} \quad (1)$$

The cumulative C mineralization was calculated as the difference between the CO_2 produced from the soil containing fine roots and that from the soil without fine root, and expressed as mg CO_2–C 100 g^{-1} soil.

Features of Soil Used for Incubation Study

The soil was alluvial in origin and come under soil order entisols, subgroup mixed loamy sand hyperthermic typic ustifluvent. The soil sample used for incubation study was collected from an agriculture field, adjacent to the block

plantations of the tree species. The soils are well drained, calcareous with 14 % of free $CaCO_3$ content and saline in reaction. The soil used for the incubation experiment had the following properties: a pH in a 1:2.5 (weight:volume) water suspension of 8.9; organic C of 3.70 g kg^{-1}. Soil samples were also collected from the block plantation of each tree species and grass species for determination of total organic C and C in resistant pool for validating the results obtained from the incubation study. Resistant organic C in soil samples were determined using the method suggested by Rovira and Vallejo [18]. In brief, one gram of oven-dry sieved (<0.2 mm) soil sample was hydrolyzed with 25 ml of 6 M HCl at 110 °C for 18 h with occasional shaking. After cooling, the un-hydrolyzed residue was recovered by centrifuging. Total C in residue left after hydrolysis was measured by dry combustion technique using Shimadzu TOC analyzer (SSM5000A) available at Indian Institute of Soil Science, Bhopal. The C in slow pool also known as acid hydrolysable pool (including active pool) was determined by subtracting acid non-hydrolysable C (biochemically stabilized C) from total organic C content of soil.

Statistical Analyses

Standard errors of the treatment means were calculated from the one-way analysis of variance (ANOVA). Multiple comparisons among means of C mineralization of different fine roots were performed with Student–Newman–Keuls test. Decomposition rate constant (k) of fine roots were calculated using the single exponential decay model of Olson [19]; $X_t/X_o = e^{-kt}$, where X_o is the original litter weight, X_t is the litter weight after a given period and t is the time. All the analyses were done using a statistical software package (SPSS window version).

Results

Fine Root Chemical Composition and Carbon Mineralization Pattern

Among the different fine roots, *Prosopis* and *Leucaena* had the highest N and lowest C/N ratios as compared to others (Table 1). Highest C content was recorded in *Acacia* and *Cenchrus* fine roots. The P, K and Na concentrations of *Jatropha* fine roots were significantly higher than those of other fine roots, but the trend was opposite for Ca content ($P < 0.05$, Table 1). Ca content of different fine root species ranged from 1.43 to 3.73 %. It was observed to be highest in *Prosopis* followed by *Acacia* (2.67 %) and *Azadirachta* (2.53 %). Total polyphenol was significantly higher in *Acacia* fine roots in comparison to others. More than four to fivefold polyphenol content in *Acacia* fine root was recorded in comparison to other species.

Addition of fine roots significantly increased the efflux of CO_2–C from soil. During 323 days of incubation, CO_2–C emission ranged from 87 to 109 mg 100 g^{-1} (0.5 g fine root amended in 100 g soil) of soil (Table 2), which corresponded to 0.07–0.12 kg CO_2–C kg^{-1} of fine root of tree species and grass. During the same period, from the unamended soil (without fine root) only 68 mg 100 g^{-1} of soil CO_2–C was released. Per cent C of fine roots of different species remaining after 323 days ranged from 75 to 85 % suggesting that only 15–25 % of C was mineralized during the incubation period. Generally, cumulative C mineralization rate of soil amended with fine roots was significantly higher than control (soil without fine root) during the entire incubation period. It ranged from 33 to 58 mg C–CO_2 100 g^{-1}soil. Over 323 days of incubation, *Acacia* fine roots had significantly higher cumulative C mineralization rate than the other individual fine roots ($P < 0.05$, Table 2). At the end of incubation, the mineralized C from *Leucaena* (17.7 %), *Azadirachta* (15.8 %), *Prosopis* (16.9 %) and *Cenchrus* (17.2 %) were significantly lower than those from *Acacia* (24.6 %) and *Jatropha* (23.8 %) ($P < 0.05$, Table 2).

Fine Root Carbon Mineralization Rate and Decay Constant

Carbon mineralization rates of fine roots of different tree species are shown in Fig. 1. Mineralization rate was very rapid in the beginning of the experiment thereafter it declined gradually over time. However, in case of leguminous species (*Leucaena, Acacia* and *Prosopis*), C mineralization rate increased up to second sampling stage (*i.e.* 22 days after incubation) thereafter it gradually decreased. Average C mineralization rate ranged from 0.34 to 0.58 mg C g^{-1} fine roots day^{-1} and followed the order; *Acacia* (0.58) > *Jatropha* (0.53) > *C. ciliaris* (0.48) > *Leucaena* (0.45) > *Azadirachta* (0.37) > *Prosopis* (0.34). Decay constant (k) for fine roots carbon ranged from 0.14 to 0.21 $year^{-1}$ under the different tree species and followed the order; *Acacia* > *Jatropha* > *C. ciliaris* > *Leucaena* > *Azadirachta* > *Prosopis* (Table 3).

Effect of Different Tree Species on Soil Carbon Pools

The total soil organic C pool varied under different tree species (Fig. 2). It was observed to be the highest (5.98 g kg^{-1}) under *P. juliflora* followed by *Azadirachta* (5.89 g kg^{-1}). Acid non hydrolysable C (biochemically stabilized C pool) of soil was also maximum in *P. juliflora* (1.84 g kg^{-1}) followed by *Azadirachta* site (1.79 g kg^{-1}). These two sites contained significantly higher total organic and biochemically stabilized C in comparison to other

Table 1 Chemical properties of fine roots of different tree species and the grass species *Cenchrus ciliaris*

Fine roots	C (%)	N (%)	C:N	P (%)	K (%)	Ca (%)	Na (%)	Phenolics (%)*
Jatropha curcas	43.4ab	1.78b	24.4	0.18b	0.29c	1.43a	0.45b	0.58a
Leucaena leucocephala	44.6bc	1.90b	23.5	0.08a	0.24bc	2.17b	0.31a	0.48a
Acacia nilotica	47.8c	1.78b	26.9	0.10a	0.24bc	2.67c	0.22a	2.62b
Azadirachta indica	40.5ab	1.75b	23.1	0.11a	0.21abc	2.53c	0.24a	0.45a
Prosopis juliflora	40.0a	1.99b	20.1	0.09a	0.20ab	3.73d	0.23a	0.78a
Cenchrus ciliaris	45.0bc	1.11a	40.5	0.10a	0.15a	1.61a	0.15a	ND

* Gallic acid equivalent, each value is mean of three replicates; ND-not determined, Means followed by the same letter are not different at 0.05 probability level using Student–Newman–Keuls test

Table 2 Cumulative carbon mineralization (mean ± SE, n = 3) from fine roots of different tree species and grass during 323 days of incubation

Fine roots	Cumulative carbon mineralization (mg C–CO_2 100 g^{-1} soil)	C mineralization (%)
Jatropha curcas	51.64 ± 3.07b	23.80
Leucaena leucocephala	39.56 ± 1.89a	17.74
Acacia nilotica	57.89 ± 3.58b	24.59
Azadirachta indica	33.35 ± 0.47a	15.85
Prosopis juliflora	34.96 ± 3.45a	16.91
Grass (*Cenchrus ciliaris*)	38.67 ± 2.61a	17.19

Note: Values in parentheses are standard error of mean; Means followed by the same letter are not different at 0.05 probability level using Student–Newman–Keuls test

sites. Soil C in mineralisable pool ranged from 3.09 to 4.14 g kg^{-1} under different tree species. Per cent of biochemically stabilized C with respect to total C was the highest (30.8 %) under *Azadirachta* and *P. juliflora sites.*

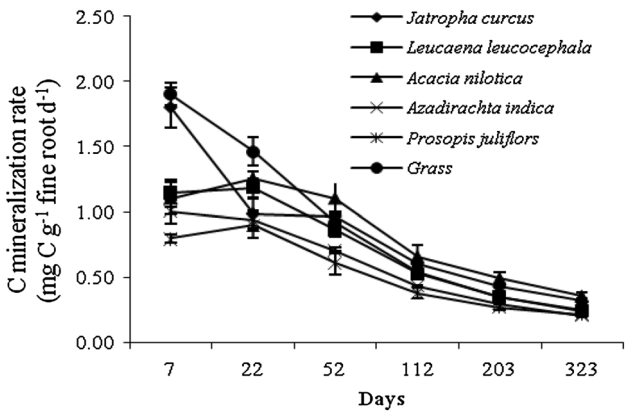

Fig. 1 Carbon mineralization rate (mg C–CO_2 g^{-1} fine root d^{-1}) of fine roots of tree species during 323 days of incubation (mean ± 1 SE, n = 3)

Table 3 Decay constant and half life of fine roots carbon under major tree species of semi-arid region

Fine roots	Decay rate ($year^{-1}$)	Half life (year)
Jatropha curcas	0.21 ± (0.08)	3.30
Leucaena leucocephala	0.17 ± (0.06)	4.09
Acacia nilotica	0.21 ± (0.08)	3.25
Azadirachta indica	0.15 ± (0.05)	4.61
Prosopis juliflora	0.15 ± (0.05)	4.76
Grass (*Cenchrus ciliaris*)	0.18 ± (0.09)	3.85

Values in parentheses are standard error of mean

Discussion

The lack of agreement between some aspects of root chemistry and root decomposition in the present investigation may also reflect greater variability within different species as reported by Hobbie et al. [20]. They reported that fine root decomposition was influenced more by root diameter (but the effects differed between the early and later stages of decomposition) and was faster for roots with high hemicellulose and cell soluble concentrations. In this study it appears that K was the governing factor which influenced the decomposition rate of fine root biomass [21].

Fine root decomposition in this study may be described as a two-stage process- an initial stage involving relatively more rapid C loss rates of labile constituents and a slower, longer period, in which much of the remaining recalcitrant C, complex plant C (e.g., polyphenols, hemicellulose–lignin) has been transformed into microbial biomass and humic substances [22]. The initial slow rate of decay up to 60 days was followed by a rapid weight loss until 120 days and then again by a phase of slow decay rate [23]. The decay constant determined by single exponential model of all the species ranged from 0.15 to 0.21 ($year^{-1}$). It suggests that only 15–20 % of fine root biomass C decomposed in a year. The value seems to be much lower as compared to the values reported for bamboo by Tripathi and Singh [24]; probably they conducted experiment under

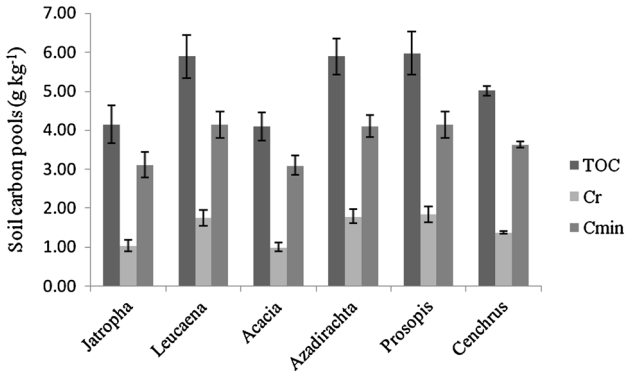

Fig. 2 Soil carbon pools (total-TOC, resistant-Cr, and mineralisable-Cmin) under different tree species (mean ± 1 SE, n = 5)

field conditions using nylon mesh bag technique. However, the decay rate value obtained in present study corresponds well with the value reported for pine and other coniferous tree species by several workers [20]. Bloomfield et al. [25] reported 40–63 % of initial root mass after one year of litterbag experiment for two woody tropical species, *Prestoea montana* and *Dacryodes excelsa*. The mean decay constant assembled by Silver and Miya [13] for conifer fine root mass loss was 0.17 ± 0.02 year^{-1} from ten studies, which is in close agreement with the present study.

Mineralization rate was rapid in the beginning of the experiment thereafter declined gradually. Mc Claugherty et al. [26] and Lõhmus and Ivask [27] also reported rapid losses of dry matter in initial phase, but after 10–20 % of the initial mass loss, the rates slowed significantly. The decrease in decomposition rate in the latter phase is probably due to rising concentrations of structural carbohydrates (such as lignin and hemicelluloses) as a result of the loss of other constituents (sugars and starches) in the detritusm [28].

The slower decomposition of roots suggested that roots have greater potential for C storage in soil. This hypothesis was reconfirmed by analyzing the total organic and biochemically stabilized C pools of soils under these species. Since the soil samples were collected from homogenous similar aged stands for determination of C in resistant pool, it gives an indirect but strong evidence of long term effect of roots on soil C stabilization. Here non-hydrolysable C has been equated with recalcitrant organic matter and its amount has been used as a measure for the resistant OM pool [29]. Total organic C content of soil was observed to be a function of biomass turnover and age of the species [30]. Since, the *Jatropha* site was only 5 years old, the total organic C content of soil was minimum (4.15 g kg^{-1}). In the remaining three sites, which were about 20 years old, significant improvement in soil C content was observed in comparison to *Jatropha* site. The higher proportion of soil C in stabilized pool under *Azadirachta* and *Prosopis* reconfirmed our hypothesis and corroborate the results of incubation study that decomposition of fine root biomass is slower in these sites as compared to other species. The slower decomposition of fine roots of *Azadirachta* and *Prosopis* provided better opportunity time for stabilization of root derived C in soil.

Conclusions

Restoration of ravenous landforms through afforestation is a well established procedure. Under such circumstances, selection of appropriate tree species with greater C stabilization potential could be the most important selection criteria. Although *P. juliflora* may have resulted in buildup of soil organic C, but due to its invasive nature and poor fodder and timber value, the species is not desirable for soil C build up. Hence, *A. indica* has good potential for stabilization of soil organic matter in the semi-arid ecosystem owing to their slow rate of fine root decomposition and higher content of biochemically stabilized soil C.

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