



Dynamics of biomass and soil carbon sequestration in *Lawsonia inermis* plantation at semi-arid region, Rajasthan, India

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ABSTRACT

Lawsonia inermis L. (Henna) is a perennial shrub cultivated as a ratoon crop in the hot semi-arid regions of India mainly for its dye-containing leaves. Considering its perennial nature, it was hypothesized that Henna plantation may sequester carbon and severe shoot pruning may affect the distribution of carbon in the above and belowground biomass. Therefore, biomass and soil carbon stock in an age-sequence of 2-, 13-, 21- and 56-year old Henna plantation was quantified to study the dynamics and patterns of carbon accumulation. The study was undertaken at ICAR- Central Arid Zone Research Institute, Regional Research Station, Pali, Rajasthan during 2017–18. Biomass and soil carbon stock significantly increased with the age of the plantation. While shoot pruning and plant populations significantly affected the distribution of carbon in the above ground and belowground biomass as well as in the soil. Within the plant system, belowground biomass stored more carbon as compared to aboveground biomass whereas, within the soil, carbon stock was higher in the lower soil layer (15–45 cm) as compared to the surface soil layer (0–15 cm). The 2-, 13-, 21- and 56-year old plantation stored about 1.60±0.44, 10.13±1.28, 10.14±1.02 and 11.42±2.50 mg biomass-C per ha respectively, with a higher rate of sequestration during early stages of the plantation.

Keywords: Allometric equation, Biomass, Carbon stock, Ratooning, Shoot pruning

Carbon dioxide (CO₂) is a major greenhouse gas responsible for about 72% of global warming (IPCC 2014). Perennial plants accumulate CO₂ in the above and belowground biomass through photosynthesis. Therefore, large-scale plantation of these plants is an effective measure to capture atmospheric CO₂ (IPCC 2014, Nair 2012). However, the potential of carbon sequestration depends upon several factors like plant species, age of the plantation, management practices, and climate and edaphic factors (Li and Liu 2014, Defrenet *et al.* 2016). Nevertheless, the determination of carbon sequestration potential of each perennial plant species becomes necessary for realizing its potential over other plant species.

Lawsonia inermis L. (Lythraceae) popularly known as henna or mehndi is a drought-hardy and evergreen medium-sized shrub. Henna is commercially cultivated in India and also in Afghanistan, Bangladesh, Saudi Arabia etc. for its leaves (Singh *et al.* 2015). The leaves contain Lawsone (2-hydroxy-1, 4-naphthoquinone), a red-orange dye, paste

made from leaves is used for dying hair and skin (Rao *et al.* 2007, Defrenet *et al.* 2016). The semi-arid climatic condition of Rajasthan is conducive for cultivation of henna, which occupies about 40,544 ha area (Government of Rajasthan 2018). Being drought-hardy in nature, its plantation provides assured income and employment to the farmers of the region (Chand and Jangid 2007).

The agronomy of henna includes transplanting of two-month-old seedlings in the well-prepared fields after the onset of monsoon from July to August. The crop starts giving returns from the establishment year itself, however, economic yields are harvested from the second year onwards (Chand and Jangid 2007). The harvested stems are used as fuel while the standing stem (portion of stem remaining in plant after shoot harvest) and entire root remain in the field until the plant is not uprooted from the field i.e. about 30–60 years. Therefore, considering, long life span, henna plantation could be a potential reservoir of biomass carbon as well as soil organic carbon. With this background, present study quantified biomass and soil carbon stock in different age-sequence of henna plantations in semi-arid region of Rajasthan.

MATERIALS AND METHODS

Study area and experimental field: The study was undertaken at the henna experimental field of ICAR-Central Arid Zone Research Institute, Regional Research Station,

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Pali, Rajasthan during 2017–18. The research station possesses 450 ha land (25°47'–25°49' E and 73°17'–73°18' N) at 217–220 m amsl. The climate of the region is hot semi-arid with about 460 mm average annual rainfall and 42°C and 7°C annual maximum and minimum mean temperature, respectively. The study was carried out in four age-sequences (2-, 13-, 21- and 56- years old) of henna plantation, planted in 2016, 2005, 1997 and 1962, respectively. All plantations were seedling planted with 6300 plants per ha as initial plant density. These plantations were rainfed and under continuous ratoon system, i.e. shoots are annually cut from 10–20 cm above the ground level for the harvesting of leaf in November. The experimental soil was sandy clay loam, having 45 cm soil depth and a dense underlying layer of murrum (highly calcareous weathered granite fragment coated with lime).

Quantification of dry biomass stock: Quadrats of 25 m² size were laid out for taking observations. Three quadrats were randomly placed in henna field and total number of plants were counted within each quadrat. From each quadrat, nine closely growing plants (three plants from three continuous rows) were selected and uprooted for the biomass study of each age group. All coarse roots (vertical and horizontally spread) were manually excavated. Shoot and root were separated from uprooted plants followed by the recording of shoot and root length and fresh weight of each component. The dry weight of biomass was determined by drying stem, root and leaf samples (taken from each uprooted plant) in a hot air oven at 80°C until constant weight.

Quantification of biomass and carbon sequestration: Annually harvested biomass (stem and leaf) may release carbon into the atmosphere and was not taken into account for the calculation of carbon sequestration. Thus, only standing biomass remaining in the field after harvest of the shoots (root biomass and unharvested stem biomass) was considered for carbon sequestration. The carbon stock per hectare area was determined by the given equation.

$$\text{Carbon stock (kg/plant)} = [\text{Dry biomass (kg/plant)} \times \text{Biomass carbon content (\%)}] / 100$$

$$\text{Carbon stock (kg/ha)} = \text{Mean of Carbon stock (kg/plant)} \times \text{Plant population (Plant/ha)}$$

$$\text{Carbon sequestration rate (Mg/ha/year)} = \text{Carbon stock (mg/ha)} / \text{Age of the plantation (year)}$$

Determination of soil carbon stock: Representative soil samples were randomly collected at three depths (0–15 cm, 15–30 cm, 30–45 cm) from each selected henna field. Separate core samples were taken for the determination of the soil bulk density. The collected samples were air-dried and sieved followed by the analysis of soil organic carbon by Walkley and Black method. The organic carbon sequestered was calculated as:

$$\text{SOC}_{\text{stock}} = \text{SOC} \times \text{BD} \times \text{D} \times (1 - \text{CP}/100)$$

$$\text{SOC}_{\text{rate}} = \frac{[\text{SOC}_{\text{stock}} \text{ of given plantation} - \text{SOC}_{\text{stock}} \text{ of 2-YOP year}]}{\text{Age of the plantation}}$$

where, SOC is the organic carbon content (%) of the fine earth (<2mm), BD is the bulk density (g/cm), D is the soil thickness (cm), CP is the coarse-particle content, and SOC_{rate} is carbon sequestration rate (mg C/ha/year).

Data analysis and interpretation: Analysis of variance (ANOVA) followed by Duncan multiple range tests (DMRT) was performed at 95% for comparing means of the obtained data. The biomass of all the excavated plants of four age groups was used to determine the relationship between plant age (independent factor) and biomass/biomass carbon (dependent factor). The best model for prediction of each biomass fraction was selected based on the highest value of the coefficient of determination (R²) among different curves.

RESULTS AND DISCUSSION

Biomass carbon stock and sequestration rate: Perennial woody plant species continuously accumulate biomass in stem and root as they age (Cheng *et al.* 2014). In the present study, the biomass and carbon stock significantly increased with increase in the age of the plantation (P<0.001) (Table 1). Strong positive relationship (R²>0.84) was obtained between biomass stock and age of the plantation (Fig 1). It is mainly due to the continuous allocation and storage of photosynthetic products in above (AGB) and belowground (BGB) biomass. Power function was found best fit equation for estimation of biomass sequestration per unit plant while polynomial function was found best fit for accumulation per unit area (Fig 1). Similar studies on increase in biomass per unit plant with the age of the plant have been widely reported (Kamau *et al.* 2008, Li and Liu 2014, Raj and Kumar 2017). The total biomass-C stock (AGB and BGB) expressed per unit plant was 34.7±9, 268±33.9, 320.9±32.4 and 871.8±190.6 g C/plant for the 2-, 13-, 21- and 56-YOP respectively (Table 1). As compared to 2-YOP, biomass-C stock per unit area was 631, 632 and 712% higher in 13, 21 and 56-YOP, respectively. Among different plant components, BGB sequestered more carbon as compared to the AGB (Fig 2). The contribution of BGB in total C-stock ranged from 62.7% in 2-YOP to 71.1% in 21-YOP.

Biomass carbon sequestration rate ranged from 15.28±1.5 to 20.62±2.6 g C/plant/year and 0.20±0.04 to 0.80±0.22 mg C/ha/year (Table 1). The sequestration rate differed significantly among the plantations as well as AGB and BGB. Young plantations (2- and 13-YOP) showed a significantly higher rate of accumulation potential per unit plant as compared to older plantations (21- and 56-YOP) (Table 1). In many tree and shrub species, same trend has been observed and this decline is generally attributed to increase in physiological constraints, decrease in soil nutrient availability and mortality etc. (Xu *et al.* 2012, Li and Liu 2014). Rate of accumulation per unit area followed a decreasing trend with increasing age, while rate accumulation per unit plant initially increased and attended plateau after 21 years of plantation (Table 1). The attained difference between biomass carbon stock per unit area and per unit plant was due to a decline in the plant population of henna with increasing age of the plantation.

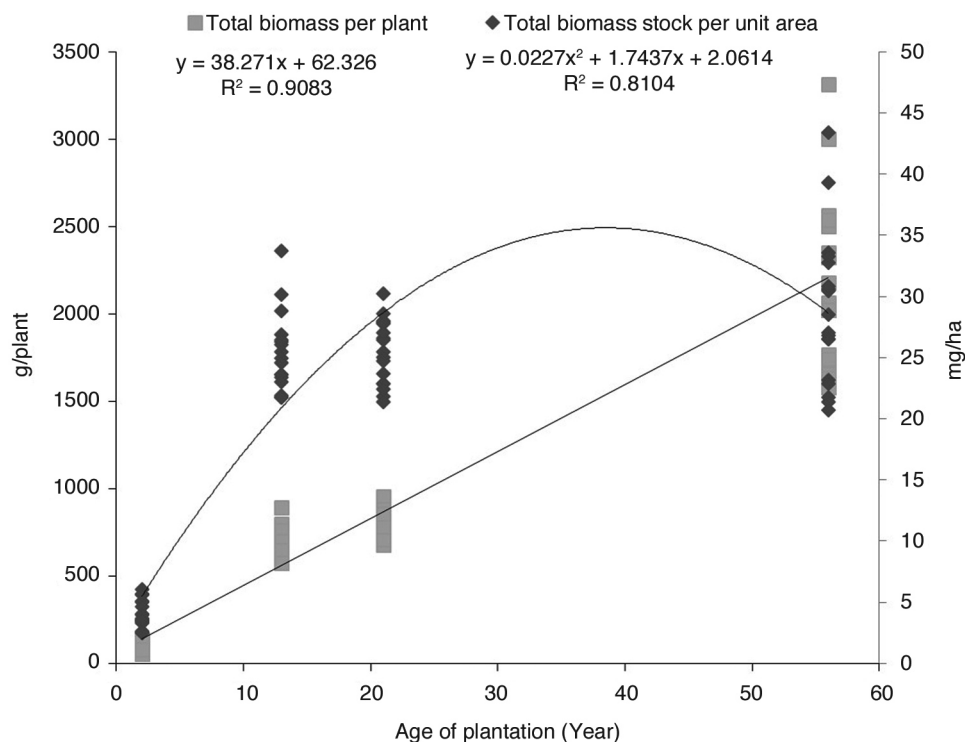


Fig 1 Relationship between age of the henna plant and biomass stock.

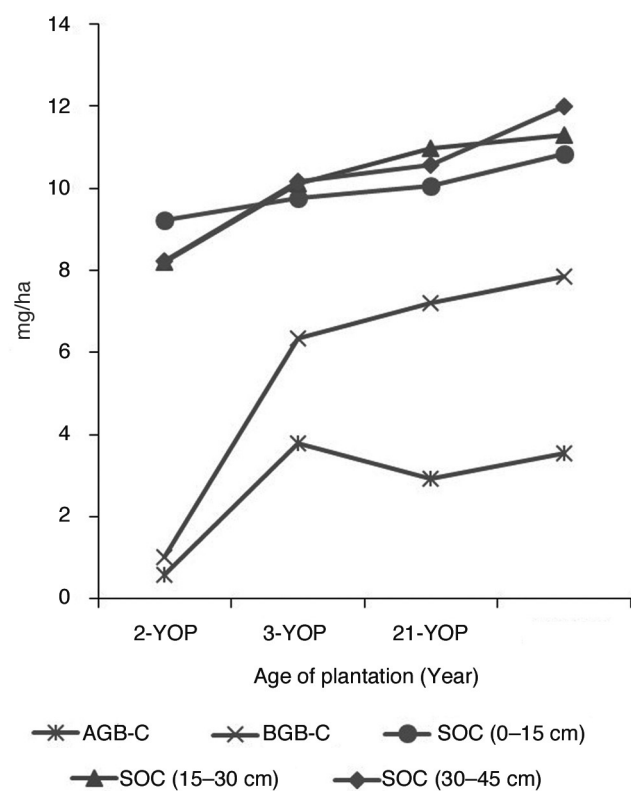


Fig 2 Trend of carbon stock in various pools of henna plantation.

The survival percentage of plants was highest in 2-YOP ($80.8 \pm 5.9\%$) which decreased with increase in the age of the plantation ($68 \pm 3.9\%$ in 13-YOP, $56.9 \pm 1.9\%$ in 21-YOP and $23.6 \pm 2.1\%$ -YOP) (Table 2). Kalita *et al.* 2016 also reported

a decline in plant population and sequestration rate per unit area with an increase in the age of the tea plantation. The extensive lateral root spread in the henna plant might be the cause for the decline in plant population due to competition for soil resources (Table 2). In plants, lateral root spreads and rooting depths generally increase as the size and life span increases. Generally, plants potentially compete belowground with other plants of the same growth form over twice the distances of maximum lateral spread (Schenk and Jackson 2002).

The henna plantation showed similar or higher total biomass-C stock as compared to similar age of tropical shrub plantation like tea (*Camellia sinensis*), however about 50% lower than *Coffea*

arabica plantation. Tea plantations store 15.65 ± 1.45 mg C/ha at the age of 22 years in North East India (Kalita *et al.* 2015, 2016) and 9.0 mg C/ha at the age of 14 years in the western highlands of Kenya (Kamau *et al.* 2008). Further, despite similar total biomass-C stock to tea plantation, the BGB-C stock of henna plantation was about 200–500% higher than total biomass-C stock of tea plantation (Defrenet *et al.* 2016, Kalita *et al.* 2016). At the same study area, 30 years old tree-based system (*Hardwickia binata* Roxb based agroforestry system) had 22.48 ± 9.5 to 31.66 ± 12.6 mg/ha total biomass-C stock (Gupta *et al.* 2019) which is about 43–60% higher than 30 year old henna plantation (13.53 mg C/ha estimated from developed equation). However, the C storage in 13-YOP Henna plantation (10.13 mg C/ha) is remarkably higher than C storage in 15 year old silvo-pastoral systems involving tree (*Acacia tortilis*) with grass (*Cenchrus ciliaris*) (6.82 mg C/ha) in arid north-western India (Mangalassery *et al.* 2014). The contribution of henna BGB in total C-stock (62.7–71.1%) was higher than AGB among a plantation of different age groups and the difference might be due to severe annual pruning of henna plant. Generally, the absolute growth rate of roots is nearly one-third that of stems in woody plant species (Niklas 2005). Comparatively, higher BGB was reported in coffee plantation (44.9%) due to its pruning in 5–6 years of rotation. Apart from this, the contribution of BGB in tea plantation has been reported to range from 10–46% among different age group of the plantation (Kamau *et al.* 2008, Raj and Kumar 2017, Kalita *et al.* 2015, 2016).

Soil carbon stock and sequestration rate: The total SOC stock also significantly increased with an increasing

Table 1 Biomass and soil carbon stock under age-sequenced henna plantation

Plantation age (Years)	Total biomass (AGB+BGB)				Total biomass-C (AGB-C+BGB-C)				Total soil organic carbon (SOC)										
	Per unit plant		Per unit area		Per unit plant		Per unit area		Per unit area		(0-45 cm)								
	Biomass stock (g/plant)	Sequestration rate (g/plant/y)	Biomass stock (mg/ha)	Sequestration potential (mg/ha/y)	Biomass-C stock (g C/plant)	Biomass-C sequestration rate (g C/plant/year)	Biomass-C stock (mg C/ha)	Sequestration potential (mg C/ha/y)	Stock (mg C/ha)	Sequestration rate (mg C/ha/y)	Mean	SD							
2-YOP	89.18a	44.59b	4.02a	2.00c	35.74a	4.95	1.60a	0.44	0.80c	0.22	25.67A	0.72	-						
13-YOP	667.68b	51.36c	25.24b	1.94c	268.01b	20.62c	10.13b	1.28	0.78c	0.1	30.03B	0.35	0.33						
21-YOP	810.22b	38.58a	25.59b	1.22b	320.92b	15.28a	10.14b	1.02	0.48b	0.05	31.60C	0.71	0.28						
56-YOP	2203.20c	471.89	39.34ab	8.43	28.85c	6.18	0.52a	0.11	871.83c	190.64	15.57a	3.4	11.42c	2.5	0.20a	0.04	34.13D	0.58	0.15

*Mean value followed by same alphabet in a column are insignificantly different (according to DMRT at P=0.05)

Table 2 Growth characteristics of *Lawsonia inermis* under different age-sequenced plantation

Plantation Age (Years)	Plant population (No. per ha)				Survival percentage				Plant height (cm)				Number of primary shoots				Root spread (cm)				Soil depth of lateral root				Carbon content (%)							
	Mean		SD		Mean		SD		Mean		SD		Mean		SD		Mean		SD		Mean		SD		Mean		SD		Mean		SD	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
2-YOP	44900a	3305	80.80a	5.95	87.80a	7.69	4.60a	1.82	58.00a	4.69	42.20a	5.50	10.00a	1.58	38.23a	0.15	43.77a	0.42														
13-YOP	37800b	2179	68.04b	3.92	110.20b	8.58	10.00b	1.58	82.67b	10.11	111.40b	22.58	18.83b	3.87	38.13a	0.31	44.03a	0.21														
21-YOP	31600c	1033	56.88c	1.86	121.80c	4.44	11.80b	1.64	88.33b	9.71	161.67c	45.09	21.00b	4.36	38.07a	0.15	44.00a	0.36														
56-YOP	13100d	1194	23.58d	2.14	126.00c	7.18	17.60c	2.70	104.60c	5.77	210.00d	10.00	27.80c	5.93	37.93a	0.15	43.73a	0.15														

*Mean value followed by same alphabet in a column are insignificantly different (according to DMRT at P=0.05)

plantation age (Table 1). This result is in agreement with other studies (Mao *et al.* 2010, Li and Liu 2014). The total SOC stock within 0–45 cm soil profiles was lowest (25.67 ± 0.72 mg C/ha) in the soil of 2-YOP and highest (34.13 ± 0.58 mg C/ha) in the soil of 56-YOP (Table 1). The total SOC stock in 0–45 cm soil profile of 13-, 21- and 56-YOP was 17%, 23% and 33% higher as compared to soil of 2-YOP. Soil sequestration rate decreased with an increase in the age of the plantation. Total SOC sequestration rate decreased from 0.33 mg C/ha/year in 13-YOP to 0.28 mg C/ha/year in 21-YOP and 0.15 mg C/ha/year in 56-YOP (Table 1). Further, the SOC stock was low in the 0–15 cm soil layer in the different aged plantation except 2-YOP (Fig 2). Generally, SOC decreases with the increase of soil depth (Raciti *et al.* 2011, Mora *et al.* 2014). The same trend was observed in the soil of 2-YOP however, the trend was not similar in other old-aged plantations (Fig 2). Organic carbon accumulation in the soil is the result of litter decomposition, secretion of root exudates and secondary metabolites and root decrepitude and death (Mora *et al.* 2014). Leaves are the main economic products of henna and are obtained by annual harvesting of the whole shoot. Removal of shoot annually from the plant thus leads to little or no leaf/stem litters on the soil surface for the decomposition. This might be the reason for lower SOC content in the 0–15 cm soil layer of 13-, 21- and 56-YOP as compared to 15–30 and 30–45 cm soil layers. The fine roots are major root litter responsible for the buildup of SOC in a deeper soil layer (Cotrufo *et al.* 2013). Lateral roots of the henna plant were concentrated within 30 cm of the soil profile and were spread up to 10 ± 1.58 cm, 18.8 ± 3.9 cm, 21 ± 4.4 cm and 27.8 ± 5.9 cm depth in 13, 21 and 56-YOP respectively (Table 2). Therefore, roots in the henna plantation may be considered as main contributors to SOC build-up. When compared to other plantations, increase in SOC stock over initial SOC content after 20 years of henna plantation in 0–30 cm soil layer (3.61 mg/ha) was about 42% lower than 20 years old poplar (*Populus euramericana*) plantation (6.22 mg/ha), however it was similar to 30 year old *Hardwickia binata* plantation on same site (Gupta *et al.* 2019).

The study found henna crop as a potential sink of carbon dioxide and significant impact of age and shoot pruning on biomass and soil carbon sequestration. The total biomass and soil carbon stock continuously increased, however, the rate of increase was dependent on the plant population. Annual shoot pruning affected the allocation of carbon that resulted in more carbon storage in belowground biomass and subsurface soil layer as compared to aboveground biomass and surface layer, respectively. This plantation can sequester about 10.14 ± 1.02 mg C/ha in biomass at the age of 21 years. These findings may help in understanding age-related changes in biomass and soil carbon as well as the adoption of henna crop in carbon farming with assured income on a large scale in arid and semi-arid regions.

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