Carbon sequestration potential of *Hardwickia binata* Roxb. based agroforestry in hot semi-arid environment of India: an assessment of tree density impact

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Agroforestry is one of the most promising options for climate change mitigation through carbon sequestration. However, carbon sequestered in agroforestry system depends on various factors like type of tree species, tree density, system age, soil and climate. One of the most important factors for enhancing carbon sequestration per unit land is tree density. *Hardwickia binata* Roxb. has been reported as suitable agroforestry tree species with multiple benefits in arid and semi-arid region, however, the role and impact of tree density in carbon sequestration is poorly reported. This study estimated impact of tree carbon density 

\[ D_1 = 333 \text{ tree ha}^{-1}, \quad D_2 = 666 \text{ tree ha}^{-1} \]

on carbon sequestration potential of 30-year-old *H. binata* Roxb. + *Cenchrus setigerus* silvipasture system in hot semi-arid region of Rajasthan. The carbon sequestered in tree biomass was estimated by reported allometric equations, whereas in soil it was determined by Walkley and Black method. Results showed significant impact of tree density on carbon sequestration per unit tree and per hectare land. The average biomass carbon sequestered by a tree was significantly more (44.5%) in low density 

\[ D_1 \] per tree 

as compared to high density 

\[ D_2 \] per tree 

system. However, total biomass carbon sequestered per hectare land was significantly more (40.8%) in high density system. The carbon sequestered in soil organic matter was higher in both 

\[ D_1 \] and 

\[ D_2 \] systems 

compared to control (sole *Cenchrus setigerus* field). It ranged from 19.93 ± 0.31 Mg C ha⁻¹ in control to 22.94 ± 0.65 Mg C ha⁻¹ and 23.25 ± 0.78 Mg C ha⁻¹ in 

\[ D_1 \] and 

\[ D_2 \] respectively. The total carbon sequestered (below and above ground tree biomass and soil organic carbon) was in the order 

\[ D_2 > D_1 > \text{control} \] in greenhouse gases (GHG) especially CO₂, CH₄ and N₂O and their atmospheric concentration which has increased by 40%, 150% and 20% respectively, since 1750 (ref. 1). Out of these GHG, CO₂ concentrations are increasing at the fastest observed decadal rate of change (2.0 ± 0.1 ppm yr⁻¹ for 2002–2011) and is the largest single contributor to global warming (>70%) over 1750–2011 (ref. 1). Reducing atmospheric concentration of CO₂ is the need of the hour for slowing down global warming and climate change. Agroforestry system has been reported as the most suitable option for achieving sustainable livelihood, climate change mitigation and adaptation. This land use system helps in mitigating climate change by sequestering large amount of CO₂ in the form of tree biomass and soil organic carbon (SOC) while also providing benefits like soil erosion control, modification of micro climate and production of resources like fodder, fuel, fruit, fibre and wood, etc.²⁻⁴.

In India, carbon sequestration potential of agroforestry systems is estimated as 0.25–7.55 Mg C ha⁻¹ yr⁻¹ for tree and 3.98 Mg C ha⁻¹ yr⁻¹ for SOC. However, this potential varies with region, types of species, age of agroforestry system, environmental condition, and previous land use history⁵⁻⁶. Livelihood of most of the farmers of arid and semi-arid region of India mainly depends on rain-fed agriculture and animal husbandry. Scarcity of fodder due to harsh climatic conditions in these regions is a major problem for farmers depending on animal husbandry. Silvipasture system becomes the most important intervention for sustainable animal husbandry in this region. *Hardwickia binata* Roxb. is a leguminous tree and is reported to enhance land use efficiency and fulfill multiple demands (timber, fodder and fuel) in arid and semi-arid regions.⁶⁻⁷. *H. binata* Roxb. based silvipasture system has also reported to sequester carbon at the rate of 2.24–3.44 Mg C ha⁻¹ yr⁻¹ (refs 4, 8, 9). However, tree density is one of the major factors that directly affects yield of intercropped species and tree biomass production/carbon sequestration under agroforestry system⁹⁻¹². Further, optimum tree density for getting maximum yield of intercropped species differs with age of the agroforestry system. Under *Prosopis cineraria* based agroforestry system, 278 and 208 trees ha⁻¹ have been reported as the optimum tree density at the age of 6–7 years and 10–11 years respectively, for obtaining maximum intercrop yield⁹⁻¹⁰. Under *H. binata* Roxb. based agroforestry system, previous studies mainly focused on quantifying impact on intercrop, biomass production and soil quality. However, impact of tree density of *H. binata* Roxb. based agroforestry on carbon sequestration in tree biomass and soil has not been reported especially in arid regions. Furthermore, quantifying carbon sequestration potential of a tree species requires conduction of a long duration experiment. Comparing carbon sequestered in already existing old-age/matured agroforestry systems may provide good

**Keywords:** Agroforestry, allometric equation, arid and semiarid regions, silvipasture, C-sequestration, tree density.

**GLOBAL warming and associated climate change is negatively impacting humans and almost all ecosystems on the earth. The main cause of this change is rapid increase**

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opportunity for identifying agroforestry systems with high carbon sequestration potential in a short duration of time. More time can be saved by switching from direct destructive estimation to an indirect method like the use of allometric equations. With this background, the objectives of the study were: (i) to determine the amount of carbon sequestered in biomass and soil in 30-year-old *H. binata* Roxb. based silvipasture systems under hot semi-arid environment of India and (ii) to quantify the impact of different tree densities on carbon sequestration and yield of intercrop species. This work aims to utilize old planted agroforestry system for better understanding of impact of tree density on carbon sequestration in matured stage of the agroforestry system.

The study was conducted in hot semi-arid environment of India, at ICAR-Central Arid Zone Research Institute, Regional Research Station (Pali-Marwar, Rajasthan) for estimating carbon sequestration in 30-year-old *H. binata* Roxb. based silvipasture system. The research station is located between 25°47′–25°49′N and 73°17′–73°18′E at 217–220 m amsl and receives 460 mm annual average rainfall with annual maximum mean temperature of 42°C and minimum 7°C. The soils were shallow in depth (30–45 cm) with sandy clay loam to sandy loam texture, 1.35–2.15 Mg m⁻³ bulk density, 7.7–8.4 pH, 0.15–0.55 dS m⁻¹ electrical conductivity and a dense underlying layer of murrum (highly calcareous weathered granite fragment coated with lime).

*H. binata* Roxb. intercropped with *C. setigerus* silvipasture systems with two tree densities, i.e. *D₁* (333 tree ha⁻¹ with 10 × 3 m spacing) and *D₂* (666 tree ha⁻¹ with 5 × 3 m spacing) were established in two replications at the station in July 1986. Each replication contained five rows of trees in *D₁* and seven rows in *D₂* with 21 trees in each row. Carbon sequestered in these 30-year-old systems were estimated by two reported allometric equations for estimating biomass of *H. binata* Roxb. grown in arid and semi-arid environment (Table 1). The total biomass carbon sequestered per hectare area was calculated on the basis of survival percentage of trees in the experiment. After flowering, above ground biomass of *C. setigerus* was harvested in 2016 and 2017 from three randomly selected plots (3 m × 10 m in *D₁* and 3 m × 5 m in *D₂*) within each inter-row space (except boundary inter-row space) for comparing dry matter yield.

Composite soil samples of three randomly sampled soils from 0 to 30 cm depth in each inter row space were collected for determining SOC. Each soil sample was collected near the base and 2.5 m and 5 m away from tree base in *D₁* and *D₂* systems. Boundary rows were avoided for the collection of soil samples. Additional soil samples from 0–30 cm depth were also randomly collected from adjoining *C. setigerus* field (control) for comparing amount of SOC sequestered under *D₁* and *D₂* systems. SOC was determined by estimating easily oxidizable organic carbon in composite soil samples by wet oxidation method as outlined by Walkley and Black. Three soil cores (10 cm depth) were randomly collected at 0–10, 10–20 and 20–30 cm depth from each inter-row space in *H₁* and *H₂* systems as well as in control for determining soil bulk density by the method outlined by Black. Further, the organic carbon sequestered in soil in 0–30 cm depth was calculated as follows

\[
\text{SOC stock (mg C ha}^{-1}\text{)} = \text{SOC (%) \times Bulk density (g cm}^{-3}\text{) \times Sampling depth (cm).}
\]

Mean of tree growth parameters, tree biomass and tree biomass carbon of both the systems (*D₁* and *D₂*) were compared by independent *t*-test while SOC stock and grass yield among *D₁*, *D₂* and control were compared by Duncan multiple range test (DMRT). All the statistical analysis was performed at 95% confidence level.

Total tree biomass (stem + root) as well as below ground tree biomass (root) estimated from both the allometric equations were slightly different, but this difference was insignificant (Table 2). Difference in below ground biomass (BGB) was almost consistent for all DBH ranges while for total biomass (TB) minimum difference was obtained for 19–20 cm DBH; beyond this, the difference increased towards both ends (Table 2). Considering a slight difference in the estimated result of

<table>
<thead>
<tr>
<th>Components</th>
<th>Equation</th>
<th>$R^2$</th>
<th>M.S.E.</th>
<th><em>P</em> value</th>
<th>Reference</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total biomass (TB)</td>
<td>0.158 (DBH)²</td>
<td>0.99</td>
<td>–</td>
<td>–</td>
<td>8</td>
<td>E1</td>
</tr>
<tr>
<td>Root biomass (RB)</td>
<td>0.036 (DBH)²</td>
<td>0.99</td>
<td>–</td>
<td>–</td>
<td>8</td>
<td>E2</td>
</tr>
<tr>
<td>Total biomass (TB)</td>
<td>0.0938 (DBH)²</td>
<td>0.95</td>
<td>48.8</td>
<td>&gt;0.0001</td>
<td>14</td>
<td>E2</td>
</tr>
<tr>
<td>Root biomass</td>
<td>0.0157 (DBH)²</td>
<td>0.85</td>
<td>6.02</td>
<td>&gt;0.0001</td>
<td>8</td>
<td>E1</td>
</tr>
<tr>
<td>Above ground biomass-C (%)</td>
<td>46% of AGB</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Below ground biomass-C (%)</td>
<td>45% of RB</td>
<td>–</td>
<td>–</td>
<td>–</td>
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Table 2. Independent sample \( t \)-test of biomass obtained from allometric equations

<table>
<thead>
<tr>
<th>Agroforestry system</th>
<th>Biomass</th>
<th>Allometric equation</th>
<th>Mean (kg tree(^{-1}))</th>
<th>SD</th>
<th>( P ) value</th>
<th>Mean difference</th>
<th>Std error difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 (10 × 3 m)</td>
<td>Total biomass (TB)</td>
<td>E1</td>
<td>253.83</td>
<td>103.67</td>
<td>0.7</td>
<td>–9.55</td>
<td>24.58</td>
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<td></td>
<td></td>
<td>E2</td>
<td>263.38</td>
<td>115.83</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Below ground biomass (BGB)</td>
<td>E1</td>
<td>53.37</td>
<td>21.56</td>
<td>0.69</td>
<td>2.03</td>
<td>4.99</td>
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<tr>
<td></td>
<td></td>
<td>E2</td>
<td>51.34</td>
<td>23.02</td>
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<td></td>
</tr>
<tr>
<td>D2 (5 × 3 m)</td>
<td>Total biomass (TB)</td>
<td>E1</td>
<td>178.06</td>
<td>68.35</td>
<td>0.9</td>
<td>–1.77</td>
<td>14.25</td>
</tr>
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<td></td>
<td></td>
<td>E2</td>
<td>179.83</td>
<td>74.05</td>
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<td></td>
<td>Below ground biomass (BGB)</td>
<td>E1</td>
<td>37.58</td>
<td>14.28</td>
<td>0.34</td>
<td>2.79</td>
<td>2.89</td>
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<td></td>
<td></td>
<td>E2</td>
<td>34.8</td>
<td>14.59</td>
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</tbody>
</table>

SD, Standard deviation.

Table 3. Tree biomass production and carbon stock in biomass and soil of the silvipasture systems

<table>
<thead>
<tr>
<th>Silvipasture system</th>
<th>Pasture yield (Mg ha(^{-1}))</th>
<th>Total biomass stock per tree (AGB + BGB (kg tree(^{-1}))</th>
<th>Total tree biomass carbon stock (AGB + BGB) (kg C tree(^{-1}) Mgc ha(^{-1})</th>
<th>CO2 sequestration potential in tree biomass (Mg CO(_2) ha(^{-1}) in 30 years)</th>
<th>Soil organic carbon stock (Mgc ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 (10 × 3 m)</td>
<td>(333 tree ha(^{-1}))</td>
<td>1.67 ± 0.14b</td>
<td>258.6 ± 109.75</td>
<td>0.78a</td>
<td>46.2 ± 23.25</td>
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<td></td>
<td>118.44 ± 50.26</td>
<td>22.48 ± 9.5</td>
<td>2.75 ± 1.16</td>
<td>82.4 ± 34.8</td>
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<td></td>
<td>81.96 ± 32.61</td>
<td>31.66 ± 12.6</td>
<td>3.87 ± 1.5</td>
<td>116.1 ± 46.2</td>
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<td></td>
<td></td>
<td>0.007</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
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<tr>
<td>Control</td>
<td></td>
<td>2.33 ± 0.30a</td>
<td>178.95 ± 71.2</td>
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<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
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Below ground biomass (BGB), above ground biomass (AGB).
\*P value: of independent t-test for equality of means (tree biomass carbon) between trees of spacing 5 × 3 m and 10 × 3 m at \( a = 0.05 \).
\**Mean value followed by same alphabet in soil organic carbon group are insignificantly different according to DMRT at \( P = 0.05 \).

Both equations, mean of biomass obtained from these two equations was used to estimate biomass C-stock.

Both systems showed similar survival percentage and about 57% of trees survived in D1 while 58% survived in D2 system. The average number of trees that survived in each row was 12 ± 1.87 and 12.14 ± 2.41 in D1 and D2 system respectively. The DBH (19.57 ± 0.46 cm) and height (8.42 ± 0.12 m) were significantly higher (16% and 7.5% respectively) in low tree density (D1) as compared to high tree density (D2) system. This led to significantly higher (44.5%) tree biomass carbon in low tree density system (118.44 ± 50.26 kg C tree\(^{-1}\)) compared to high tree density system (81.96 ± 32.61 kg C tree\(^{-1}\)) (Table 3). In spite of higher biomass carbon stock per tree in low density agroforestry system, tree biomass carbon stock per hectare was significantly higher (40.8%) in high tree density system (31.66 ± 12.6 Mgc ha\(^{-1}\)) compared to low tree density system (22.48 ± 9.5 Mgc ha\(^{-1}\)) (Table 3). D1 and D2 system sequestered about 82.4 ± 34.8 Mg CO2 ha\(^{-1}\) and 116.1 ± 46.2 Mgc CO2 ha\(^{-1}\) respectively, in 30 years with annual sequestration potential of 2.75 ± 1.16 Mgc CO2 ha\(^{-1}\) yr\(^{-1}\) and 3.87 ± 1.54 Mgc CO2 ha\(^{-1}\) yr\(^{-1}\) respectively (Table 3). The dry biomass yield of C. setigerus was about 30% less in both D1 and D2 compared to sole C. setigerus field (2.33 Mgc ha\(^{-1}\)) (Table 3). However, there was insignificant difference in dry biomass yield between both systems [D1 (1.67 Mgc ha\(^{-1}\) and D2 (1.57 Mgc ha\(^{-1}\))] indicating D2 system has significantly higher tree biomass carbon sequestration potential per hectare land without significant reduction in C. setigerus dry biomass yield.

Both silvipasture systems showed insignificant difference in SOC stock (D1 22.94 ± 0.65 Mgc ha\(^{-1}\) and D2 23.25 ± 0.78 Mgc ha\(^{-1}\)); however, both had significantly higher SOC-stock (15.8%) compared to control (19.93 ± 0.31 Mgc ha\(^{-1}\)) (Table 3 and Figure 1) in 0–30 cm soil depth. There was significant difference in total carbon sequestration (biomass + soil) among D1, D2 and control. The total carbon sequestered per hectare land was highest in D2 (54.8 ± 5.6 Mgc ha\(^{-1}\)) followed by D1 (45.5 ± 4.3 Mgc ha\(^{-1}\)) and sole C. setigerus field (19.93 ± 0.31 Mgc ha\(^{-1}\)) (Figure 1). In D1, carbon sequestered in biomass and soil was almost similar, while in D2, carbon sequestered in biomass was more compared to soil (Figure 1). The contribution of AGB, BGB and soil in total carbon sequestration was 40%, 10% and 50% in D1 and 46%, 12% and 42% in D2 respectively (Figure 1).

Higher growth and biomass carbon of individual tree in low density system (D1), compared to high density (D2) may be due to less competition for resources like water, nutrients and/or low shading effect of adjoining tree row. Agroforestry system with high tree density has reported lower tree growth, tree biomass and inter crop yield compared to low density system mainly due to competition for resources\(^6\)\(^-\)\(^12\). However, high tree density system produced more tree biomass per hectare area compared to
low density system due to more number of trees per unit area. This indicates that an individual tree may sequester more biomass carbon in low density plantation; however, total biomass carbon stored per hectare area depends on tree density. Therefore, optimum tree density is required for highest gain for both, tree biomass as well as yield of intercrop. In the present study, total tree biomass yield was 258.60 ± 109.75 kg tree⁻¹ in low density system (333 tree ha⁻¹) while 178.95 ± 71.20 kg tree⁻¹ in high density system (666 tree ha⁻¹). However, Singh and Singh

The study found significant effect of tree density on carbon sequestration in agroforestry system. A system with high tree density had less C-accumulation in an individual tree compared to a low density system; however, total carbon sequestered per hectare area was significantly more in a high density tree system. Tree spacing has also been reported to affect the yield of intercrop as well as tree due to competition and shade effect, which increases with the age of system. Therefore, determination of optimum tree density is necessary for getting maximum benefits in terms of carbon sequestration, intercrop and tree yield. In this study, established old agroforestry systems with different tree densities provide a good platform for determining carbon sequestration potential along with identification of better tree density for climate change mitigation and adaptation. In this, study H. binata Roxb. based agroforestry system with high density (666 tree ha⁻¹) was found suitable for enhancing carbon sequestration per hectare land over low density system and sole crop land. This system can sequester about 116.1 ± 46.2 Mg CO₂ ha⁻¹ in biomass with 58% survival rate in 30 years.


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Myco-potash solubilizers

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This study was carried out to evaluate the efficacy of agriculturally beneficial fungi for potash solubilization and to develop myco-potash cultures for use in crop growth. In all six fungal cultures were utilized in the study, viz. *Paecilomyces lilacinus*, *Tricoderma harzianum*, *Aspergillus wentii*, *Emericella nidulans*, *Verticillium lecanii* and *Tricoderma viride*. Among them, *A. wentii* and *T. viride* were found to produce 3.3 and 3.65 mm solubilization index around the colony after 7 days of incubation (DAI) on Aleksandrov medium supplemented with mica as potash source. Whereas for agar medium supplemented with feldspar, maximum solubilization index was 2.5 mm (*A. wentii*), 2.55 mm (*T. viride*), 2.48 mm (*V. lecanii*) and 2.58 mm (*P. lilacinus*) 7 DAI. To reveal the mechanism of potash solubilization, *A. wentii*, *T. viride*, *T. harzianum* and *V. lecanii* were chosen for organic acid profiling using HPCL. *A. wentii* produced the highest amount of total organic acid (1847.775 μg/ml).

Keywords: Fungal cultures, myco-potash, organic acids, solubilization index.

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