Carbon Sequestration Study at Eco-restoration Sites of BCCL

(Tetulmari - 8 ha & Damoda - 7 ha)

Submitted by

Department of Environmental Science & Engineering

Centre of Mining Environment

(A Centre of Excellence by MOEF & CC, GOI)

INDIAN SCHOOL OF MINES

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P R E F A C E

The research study entitled"**Carbon Sequestration Study at Ecorestoration sites of BCCL (Tetulmari 8.0 ha & Damoda 7.0 ha)"** sponsored by Bharat Coking Coal Limited (BCCL), Dhanbad, has been carried out by the Department of Environmental Science & Engineering (Centre of Mining Environment), Indian School of Mines, Dhanbad. For estimation of Carbon sequestration of ecorestoration sites located at Tetulmari (Sijua area), Damoda old Ghutway and Damoda inclined Ghutway sites of BCCL, field survey was carried out during March 2015- July 2015. Carbon stock was estimated for biomass of vegetation, litter and mine soil components and converted to CO_2 equivalent and expressed as tons of CO_2 sequestered per hectare. As the ecorestoration sites are very young (hardly 3 years old), it is expected that CO2 sequestration will increase substantially with age of vegetation. I am sure that the outcome of the study will help the mining companies to further strengthen their ecorestoration techniques to enhance CO_2 sequestration. I am highly indebted to M/s Bharat Coking Coal Limited (BCCL), Dhanbad for awarding CO_2 Sequestration project to ISM, Dhanbad.

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ABBREVIATIONS

AGB – Aboveground Biomass
BCCL - Bharat Coking Coal Limited
BD – Bulk Density
BGB – Belowground Biomass
C – Carbon
Ca – Calcium
CEC – Cation Exchage Capacity
CHNS – Carbon Hydrogen Nitrogen & Sulphur
CO2 – Carbon dioxide
CRM – Certified Reference Material
CS – Carbon sequestration
Damoda Site -1- Damoda Old Ghutway Ecorestoration Site (4 ha)
Damoda Site -2- Damoda Inclined Ghutway Ecorestoration Site (3 ha)
DBH – Diameter at Breast Height
EC – Electrical Conductivity
FAO – Food and Agriculture Organization
FRI - Forest Research Institute
H_2SO_4 – Sulphuric Acid
HCL – Hydrochloric acid
IC – Inorganic Carbon
JCF – Jharia Coalfields
K – Potassium
Mg – Magnesium
Mo – Molybdenum
N – Nitrogen
Na – Sodium
O- horizon – Organic matter horizon
OB – Overburden
OC – Organic Carbon
OM – Organic Matter
P – Phosphorous
RB – Root Biomass
RMS – Reclaimed Minesoils
SnCl2 – Stannous Chloride
SOC – Soil Organic Carbon
SOM – Soil Organic Matter
TSC – Total Soil Carbon

EXECUTIVE SUMMARY

1.0 Ecorestoration is the process of assisting the recovery of structural and functional components of ecosystem, which has been destroyed or degraded by mining activities. In this process, a 3-tier vegetation cover is developed (herbs- grasses and legumes; shrubs and trees) which will slowly restore the food chain, increase fertility of site through humus formation and restore biodiversity due to amelioration of habitat. In contrast, tree plantation aims to develop greenery on the degraded site by planting hardy fast-growing tree species, which ends up with monolayer canopy cover without considering the ecological aspects. To combat global warming, The Kyoto Protocol proposed that carbon reduction could take place by decreasing fossil fuel emissions, or by accumulating carbon in vegetation and soil of terrestrial ecosystem. Therefore, the aim of the present study is to estimate CO_2 sequestration of the ecological restoration sites of Bharat Coking Coal Limited (BCCL).

2.0 Terrestrial Carbon sequestration is the process of (i) transforming or transferring atmospheric CO_2 through photosynthesis into biomass components such as trees, shrubs, vegetation, and soil organic matter (SOM), and (ii) incorporation of biomass into the soil as humus. This leads to the effective storage of atmospheric CO_2 in these components. In Ecorestoration sites, the carbon sequestration can be assessed by adding all components of carbon pool in the ecosystem i.e., SOC (soil organic carbon) content at 0 to 15 cm depth, carbon stored in aboveground biomass (AGB) and belowground biomass (BGB) or root biomass (RB), and litter Carbon.

3.0 For estimating the tree biomass, non- harvest technique i.e., regression or allometric equations was used. In this process, tree biomass is directly estimates by using with the Diameter at Breast height (DBH) values (Brown, 1997). Allometric equations have been used throughout the world for the estimation of the AGB and BGB and also the C fixed within these components.

4.0 Under this study, field survey of 3 sites (Tetulmari, Damoda dump site 1 and 2) was carried out 2 times: (1) 12.03.2015 during onset of summer and (ii) again on 25. 07.2015, along with BCCL officials to assist the survey team and sample collection. The carbon sequestration in the ecorestoration sites were evaluated by comparing with two sites; (i) an un-reclaimed coalmine overburden dump at Katras colliery, and (ii) a natural forest site near Damoda colliery. Total area of Tetulmari site was 8 ha, while Damoda old Ghutway site (denoted as Damoda site 1) and Damoda inclined Ghutway site (denoted as Damoda site 2) was 4 ha and 3 ha respectively.

5.0 In Tetulmari ecorestoration site, 9 quadrates were laid down (5.5 m x 5.5 m) for measurement of relative density and DBH of tree species. Similarly 3 no of quadtrats (10 m x 10 m) were laid down at Damoda ecorestoration site 1 and two nos (10m x 10 m) at Damoda ecorestoration site 2.

6.0 **Ecological survey** of all the three ecorestoration sites consists of identification of tree species, counting total no of individual species present in each quadrates and measurement of DBH. Plant community parameters, like frequency of occurrence, density and relative density, and abundance of species were calculated. The DBH of tree species were classified according to their diameter classes, and average DBH value was used for the calculation of above ground biomass (AGB) using allometric equations (Brown et. al. 1997). The root biomass (RB) was calculated by the equation given by MacDicken (1997). Small saplings (< 1.5 m height) were not considered for calculation of biomass and carbon sequestration (CS). All bamboo vegetation was considered for CS study.

7.0 **Litterfall** was collected from all the 3 sites by using a metal quadrat of 50 cm x 50cm underneath different tree species, bamboo and grass litter. The litter was dried at 80 ^{0}C in a hot air oven and reported as t/ha. The CS was estimated by considering 40% of C.

8.0 **Soil samples** were collected using standard sampling methods recommended for sampling of reclaimed coalmine overburden dumps. All the samples were collected from 0-15 cm depth with 3 replicates. The physicochemical parameters such as – soil fractions, pH (1:1, 1:2.5; w/v); electrical conductivity, bulk density, moisture content, soil organic carbon, available N, P, CEC, exchangeable cations, and base saturation were analyzed by standard methods.

9.0 Ecorestored dump sites showed **3- tier vegetation growth** characterized by trees, shrubs, herbs and grasses. In all the three ecorestored dumps Shisham (*Dalbergia sissoo*) was dominant species, followed by Siris (*Albizzia spp*) and Bamboo. Other common species were Palash (*Butea monosperma*), Chatim (*Alstonea scholaris*), Neem (*Azadirachta indica*), *Dodonea viscosa*, Jamun (*Syzygium cumini*), *Peltaphorum pterocarpum*, *Phyllathus emblica*, *Ficus recemosa, Pongamia pinnata, Zizyphus mauritiana, Ficus infectoria, Bauhunia* spp, *Trema orientalis*, etc.

10.0 **Estimation of total tree density**: The total biomass of tree strands consist of above ground (shoot) biomass and root biomass, which was calculated by using Allometric equations. Tree density of the three sampling sites were measured by using a quadrat and density was found as 1947 nos /ha in Tetulmari site to as high as 2850 nos/ha in Damoda – 2 site. These values are very higher due to pollination and seed broadcasting germination and also additional plantations are carried out every year in these sites.

11.0 **Estimation of average tree biomass including bamboo and carbon sequestration**: Total biomass of tree species (AGB + RB) were calculated for the 3 ecorestoration sites by using

allometric equation and values were used for the estimation of carbon sequestration (CS). Maximum total biomass was calculated as 77.466 t/ha in Tetulmari site followed by 28.896 t/ha in Damoda -1 and 34.61 t/ha in Damoda-2 site. Highest value of CO_2 sequestration rate (t/ha) was observed in Tentulmari restoration site, due to presence of some mature *Dalbergia sisoo* plants (142.15 t/ha)> Damoda -2 (63.51 t/ha)> Damoda-1 (53.02 t/ha) > unreclaimed dump (9.61 t/ha), while for reference forest site, total biomass was found highest (130.20 t/ha).

15.0 **Estimation of carbon sequestration by litter accumulation**: Average litterfall accumulated underneath different trees and grass species were calculated for three ecorestoration sites measured as 3.77 t/ha, 2.45 t/ha and 2.73 t/ha respectively. These values were converted into carbon stocks and rate of carbon sequestration (CS) by the litter amount for three sites were calculated as: 5.533 t CO_2/ha (Tetulmari), 3.592 t CO_2/ha (Damoda-1) and 4.007 t CO_2/ha (Damoda-2), which is lower than reference forest (5.65 t CO_2/ha) but higher than unreclaimed site (1.145 t CO_2/ha).

16.0 **CO_2 sequestration in reclaimed mine soil**: The physicochemical parameters of soil samples collected from the Ecorestoration sites, un-reclaimed site (Katras colliery) and natural forest (Damoda area) were analyzed by the standard methods and carbon (C) stock was calculated using standard equation (Mg C ha^{-1} = [%C * Corrected B_d * d (m) *10^4 m^2 ha^{-1}] /100 (Lal et al., 1998). This equation uses the corrected bulk density of soil (obtained after removal of coarse fraction of soil) and the biogenic carbon (free of inorganic matter and coal carbon). CO_2 sequestration by mine soil was calculated as follows: 65.65 t CO_2/ha (Tetulmari), 59.93 t CO_2/ha (Damoda-1), 46 t CO_2 /ha (Damoda-2), 28.85 t CO_2 /ha (unreclaimed dump) and 130 t CO_2 /ha (reference forest site).

17.0 **Comparative study of CO_2 sequestration (CS) at the ecorestoration sites**: Comparison of CO_2 sequestration in Tetulmari, Damoda site 1 and Damoda site 2 with unreclaimed dump (Katras colliery) and reference forest site (Damoda natural forest) revealed that CS at the natural forest site was found highest (378.52 t CO_2/ha) as compared to other ecorestoration sites, Tetulmari ecorestoration site (213.33 t CO_2/ha) > Damoda old Ghutway ecorestoration site 1 (116.54 t CO_2/ha) > Damoda inclined Ghutway ecorestoration site 2 (113.52 t CO_2/ha) > unreclaimed dump (47.63 t CO_2/ha). The contribution of CO_2 sequestration by different components is given in **Table-1**.

Table 1: Comparative study of carbon sequestration of three ecorestoration sites (Tetulmari, Damoda site 1 and Damoda site 2), un-reclaimed coalmine dump and natural forest site (Damoda area).

Sl no.	CO_2 sequestration by different components	Tetulmari Ecorestoration Site*	Damoda -1 (Old Ghutway)*	Damoda-2 (inclined Ghutway)*	Unreclaimed overburden dump	Natural forest site
1	Aboveground & Belowground biomass (t/ha)	142.15	53.02	63.51	17.63	242.587
2	Litter fall (t/ha)	5.533	3.592	4.007	1.145	5.65
3	Soil (t/ha)	65.65	59.93	46.00	28.85	130.285
	Total CO_2 sequestration (t/ha)	213.33	116.542	113.517	47.625	378.522

* assumed age of ecorestoration is about 3 years

18.0 Conclusions

Ecorestoration process is better alternative than sample plantation, because it leads to reinstatement of ecosystem in the degraded site. Due to development of 3-tier canopy over in the ecorestoration site, it not stabilizes and minimizes pollution but also these sites act as potential sink of CO_2. The accumulation of C stock will also be increased in biomass and minesoil components, with the gradual increase in age of ecorestoration, since these ecorestoration sites are very young (hardly 3 years old). The overall CO_2 sequestered by all components in the three ecorestoration dumps was calculated as: Forest area (378 t CO_2/ha)> . Tetulmari site (213 t CO_2/ha) > Damoda old Ghutway (116 t CO_2/ha) > Damoda inclined ghutway (113 t CO_2/ha) > unreclaimed site (48 t CO_2/ha). It is expected that, after 5 years, CO_2 sequestration in Tetulmari will be in order of 350 t/ha and other sites in the range of 190-210 t/ha.

19.0 Recommendation and Scope for future work

Some more additional plantation may be done in the periphery of the restoration sites as well slope area. While selecting the species, more native evergreen tree species should be preferred. Additionally few climbers (lianas) may be planted, so that it will mimic the natural forest. At few places, topsoil materials may be applied, to speed up the natural colonization process. It is recommended that, as CO_2 sequestration depends on nature of substrate, height and slope of the dump, geo-climatic condition of the area, type and age of vegetation, therefore, few more field studies should be conducted for better assessment and prediction of CO_2 sequestration.

1.0 INTRODUCTION

Ecorestoration is the process of assisting the recovery of structural and functional components of ecosystem, which has been destroyed or degraded by mining activities. In this process, a 3-tier vegetation cover is developed (herbs- grasses and legumes; shrubs and trees) which will slowly restore the food chain, increase fertility of site through humus formation and restore biodiversity due to amelioration of habitat. In contrast, tree plantation aims to develop greenery on the degraded site by planting hardy fast-growing tree species, which ends up with monolayer canopy cover without considering the ecological aspects. To combat global warming, The Kyoto Protocol proposed that carbon reduction could take place by decreasing fossil fuel emissions, or by accumulating carbon in vegetation and soil of terrestrial ecosystem. Therefore, the aim of the present study is to estimate CO_2 sequestration of the ecological restoration sites of Bharat Coking Coal Limited (BCCL).

Carbon (C) sequestration is defined as "the process of increasing the C content of a C pool other than the atmosphere" (IPCC 2000). All components of the ecosystem such as oceans, geological formations, plants and soil can act as 'carbon sink' by allowing more storage of C than its flow out of these systems as CO_2. Thus, there are three primary types of C sequestration system: (i) Geological, (ii) Ocean, and (iii) Terrestrial ecosystem. The flow of C is measured in tons [1t C = 1 Mega or Million gram C (Mg C)], gigatons [1GtC = 1 billion metric tons or 10^9 tons C].

Terrestrial C sequestration is the process of (i) transforming or transferring atmospheric CO_2 through photosynthesis into biomass components such as trees, shrubs, vegetation, and soil organic matter (SOM), and (ii) incorporation of biomass into the soil as humus. This leads to the effective storage of atmospheric CO_2 in these biomass components until decomposition of biomass into the soil. Soil contains approximately 75% of the terrestrial C pool three times more than the amount stored in living plants and hence it plays a vital role in the global C cycling (Schlesinger and Bernhardt 2013).

During the process of coal surface mining, vegetation cover is completely stripped, and soils and overburden (OB) rocks are removed to reach the coal-bed generating huge volume of

heterogeneous mass, which are stored as overburden dumps (external dumps) or used as backfill material for open cast voids (internal dumping). These OB dumps, initially devoid of soil organic carbon (SOC), and further reclaimed into a forest land. Establishment of vegetation with high biomass production in reclaimed minesoils (RMS) reduces soil degradation and improves SOC with time. Thus, reclaimed coalmine dump acts as a viable alternative to terrestrial C sequestration.

Carbon sequestration through planted forests serves as a sizeable sink for atmospheric CO_2 both in temperate and tropical regions (Houghton et al., 2000; Fang et al., 2001). Sequestration of carbon has received considerable attention in recent past as a result of its global commoditization. Plantation programs can be used to create carbon credits which can generate significant income for developing countries (Niles et al., 2002). Though, accurate measurement of forest carbon sink is difficult without the precise estimation of biomass.

In the RMS, the C pool can be assessed by adding all components of C pool in the ecosystem: SOC at 0 to 15 cm depth, aboveground biomass (AGB) C, belowground biomass (BGB) or root) C, and litter C Shrestha and Lal (2010). Aboveground biomass consist of stem wood, stem bark, foliage, branches, and leaves whereas the litter layer consists of dead trees and wood, and forest floor (detritus, shed vegetative parts in various stages of decomposition above the mineral soil surface). The SOC concentration was converted to SOC pool by multiplying with its bulk density (BD) and soil depth. Whereas concentrations of belowground biomass (root), litter, and aboveground biomass C were converted to their respective C pools by multiplying biomass per hectare with their C concentrations respectively. Diameter at breast height (DBH) is the most commonly used parameter for calculating aboveground tree biomass of respective tree species

Trees often represent the greatest fraction of total biomass of a forested area, with other carbon pools only a fraction of the total tree biomass. The understorey is estimated to be equivalent to 3% of above-ground tree biomass (AGB), dead wood 5-40%, and fine litter only 5% of that in the AGB. Belowground biomass (BGB) or root biomass is more variable, ranging between 4 - 230%, and can be more than two times greater than that in the above-ground tree biomass (Brown, 1997). AGB in trees also responds more rapidly and significantly as a result of

land-use change than other carbon pools. As a consequence, the majority of carbons accounting efforts are focused on tree AGB, for which there is a considerable forest science research base.

Two approaches for estimating the biomass density of tree biomass exist and are more commonly applied. The first directly estimates biomass density through biomass regression or allometric equations. The second converts' wood volume estimates to biomass density using biomass expansion factors (Brown, 1997). Allometric equations are generally used for the estimation of biomass stock of tree species, which relates easily the measured independent variables (like, DBH) and provide a relatively accurate estimate. Forms of the general allometric equations vary widely; however, the most commonly used is a linear equation as follows (Dudley and Fownes, 1992):

y = a + bx Where, y = biomass, and x = diameter at the breast height (DBH)

The use of allometric equations is a crucial step in estimating above and belowground biomass (Brown et al., 1989). Whereas; biomass depends on the various factors such as, age of the stand, species and topography. Errors in estimates of biomass stocks were also believed to result from absence of allometric equations for higher diameter classes in general and for the smaller diameter class in particular (below 10 cm) which have fast growing rate than the higher diameter class trees.

Direct tree harvest data is difficult to obtain and very less numbers of studies are available in the literatures. In India, several authors have been published biomass estimations using allometric equations for a few tree species and for the diameter above 10cm at breast height (Lodhiyal et al., 2002). In this report, non harvest technique and allometric equations are used to estimate biomass and carbon sequestration rates of different plant species extensively considered for plantation programs in mine reclamation owing to their economic and ecological values and high survival rate. This report also focuses on the distribution of sequestered C in different components of minesoils (SOM, aboveground and belowground biomass, litter) and also total rate of C sequestered in different ecologically restored sites.

2.0 DESCRIPTION OF THE STUDY AREA

C-sequestration potential study was carried at three ecological restored coalmine overburden dumps undertaken by Bharat Coking Coal Limited (BCCL). These sites are located in the central part of Jharia coalfield which is characterized for the long history of land degradation, hostile climatic conditions, different tree species composition and slow succession process. A 3-tier plantation of grasses, shrubs and several tree species (natural vegetation of nearby forest) were started before the onset on monsoon in the year 2012 by the BCCL in association with Forest Research Institute (FRI), Dehradun. Thus, the age of the entire restored site is 3 years.

1. **Tetulmari ecorestoration site:** The dump site of 8 ha located in Tetulmari colliery, Sijua area V of Jharia coalfields.
2. **Damoda old Ghutway ecorestoration site :** The dump site of 4 ha located in Damoda colliery, Barora area It is denoted as **Damoda ecorestoration site 1.**
3. **Damoda inclined Ghutway ecorestoration site: T**he dump site of about 3 ha area in Damoda colliery, Barora area. It is denoted as **Damoda ecorestoration site 1.**

Additionally, two reference areas were also selected in the vicinity of the ecorestoration coalmine dumps to compare the carbon sequestration of these three sites.

4. **Un-reclaimed reclaimed coal mine overburden dumps** at Katras areas; and
5. **Forest area** (Reserve forest near Damoda area), treated as reference site.

2.1 Tetulmari Ecorestoration site, Sijua area.

This study was carried out in the Ecorestoration coalmine dump site of Tetulmari colliery, Sijua area V, Jharia Coalfield (JCF) located in the Dhanbad district of Jharkhand, Eastern India. It falls between latitudes 23º48´5´´N - 23º48´15´´N and longitudes 86º20´25´´E - 86º20´40´´E (**Figure 1**). The climate is tropical with a summer average temperature of 44.5ºC and a winter average temperature of 20ºC. The monsoon sets between June to October and 80-85% of annual rainfall is received during monsoon season. The annual average rainfall for the last ten years is 1598 mm per year.

The ecologically restored overburden dump at Tetulmari colliery, Sijua area was visited first time by the ecorestoration expert team of the Indian School of Mines, Dhanbad during the

winter season (on date 28.02.2015). During the field visit species diversity were documented and soil samples were collected. The dump site showed dense 3- tier vegetation growth (trees, shrubs and grasses) with different types and heights from a distance **Photo 1(a)**. The distance view of ecologically restored overburden dump can be seen from the entrance gate of the dump base is shown in **Photo 1(b)**. The site was visited before the onset of summer season (on date 12.03.2015) by the team of experts during which both soil samples and litter were collected underneath various tree species. The third visit was carried out during monsoon season on 17.07.2015, when only quadrat sampling was done for the assessment of biodiversity parameters. The ecologically restored site has dense tree growth of different shrubs and trees along the pavement laid down for walking through the ecorestoration site (**Photo 2**).

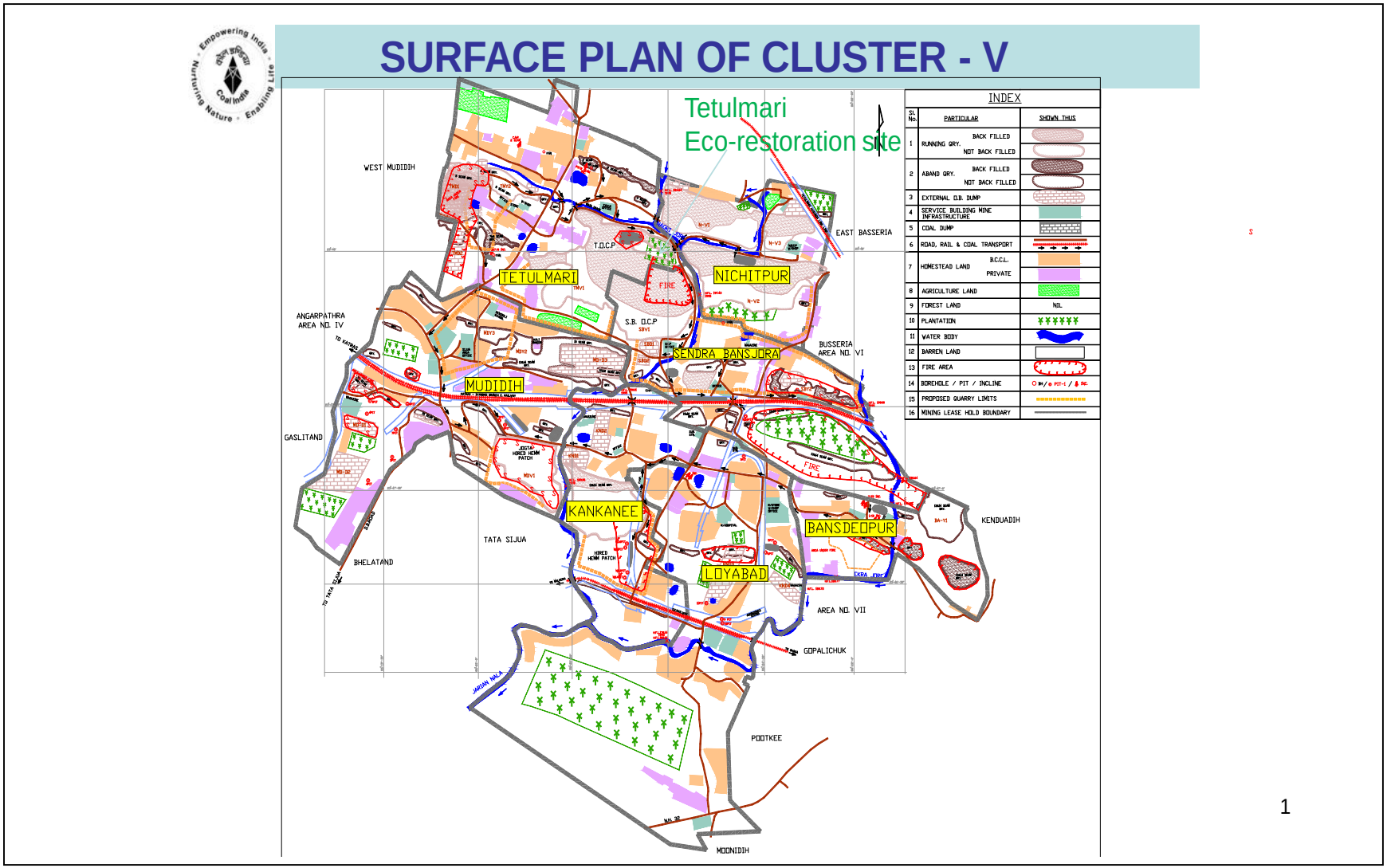

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Figure 1: Location map of Tetulmari ecorestoration site

Photo 1(a): Three-tier vegetation growth (trees, shrubs, herbs and grasses) at Tetulmari ecorestoration site

Photo 1(b): Photograph showing team of ISM Dhanbad, visited the ecological restoration site of Tetulmari. Team members from left to right are: (i) Rimi Das (Research Scholar), (ii) Prof. S. K. Maiti (HOD, ESE dept), (iii) daily worker, (iv) Jitendra Ahirwal (Research Scholar), (v) Bir BahadurSingh

Photo 2: Close view of Tetulmari ecorestoration dump showing dense growth of different shrubs and trees as well as the pavement laid down for walking through the ecorestoration site.

Photo 3: Close view of shisham (*D. sissoo*) growing on the Tetulmari Ecorestoration dump. The pipe laid down on the boulder surface shows the process of watering the vegetation from the fixed water storage tank located at the dump

Dominant vegetation of *Dalbergia sisoo* (shisham) with DBH range from 3-21 cm includes both saplings and old shisham trees were found at the dump site. At the initial stage of plantation watering system was established at the restored dump site. The white coloured pipe laid down on the boulder surface shows the process of watering the vegetation from the fixed water storage tank located at the top of the dump. Close view of *Dalbergia sisoo* (shisham) grown and watering system on the ecorestoration dump site is shown in **Photo 3.**

Growth of the plant saplings such as, shisham and bamboo were also observed in the restored dump. Bamboo clumps and their undergrowth vegetation in the dump were found be satisfactory (**Photo 4a**). Some of the old tree species were already present in the dump which had DBH >15 cm but may not be the part of plantation, such as the growth of old shisam tree (**Photo 4b)**, and the reminiscent of old Palash (*Butea monosperma*) tree in the dump **(Photo 4c**). Shisham trees of different height were found on the restored dump which contributes to the dominant vegetation of the dump and the growth of the other species can also be seen in the background (**Photo 5).** The mulch of the perennial grasses and other undershrub's covered the Ecorestoration site. These dry grasses are decomposed during monsoon and contribute to increase in soil organic carbon and nutrient content (**Photo 6**).

During the field visit, some of the scanty vegetation were seen at the ecorestoration dump, which includes Bakain (*Melia azedarach*), Pakur (*Ficus infectoria*) etc. (**Photo 7a & b)**. Since Pakur was a small tree, accumulation of very less litter was observed beneath this tree species. Other species found were Neem (*Azadirachta indica),* Kanchan **(***Bauhunia variegata*), Karanj (*Pongamia pinnata),* Copper pod (*Peltaphorum pterocarpum),* Amla *(Phyllanthus emblica*) etc. The dominant growth of Hop bush or Vilayti mehendi (*Dodonaea viscosa*), an evergreen sturdy shrub was observed on the dump. **(Photo 7c).**

At an earlier stage, major portion of the ecorestoration dump was covered with the Deenanath (*P. pedicellatum)* and other grasses, like *Cenchrus ciliaris, Cenchrus setigerus, Cynodon dactylon, Saccharum munja, S. benghalense* etc., which dried up and formed a thick mulch cover (litter layer) on the dump surface. A close view of the dry mulch of Deenanath and other grasses in the restored site is shown in **Photo 8(**a-b). This dry mulch or grass litter layer was collected by a metal quadrate of 50 cm x 50 cm and minesoil samples are collected after removal of litter (**Photo 8c**). Quantity of litter fall amount was then expressed as per hectare area and later used for the calculation of carbon sequestration. The distribution of root and shoot biomass of Deenanath grass was estimated by uprooting a whole clump (**Photo 8d**). It was found that, shoots contribute maximum biomass (85%) than root parts (15%). In other places of the dump, litter fall contributed by tree species was found minimum.

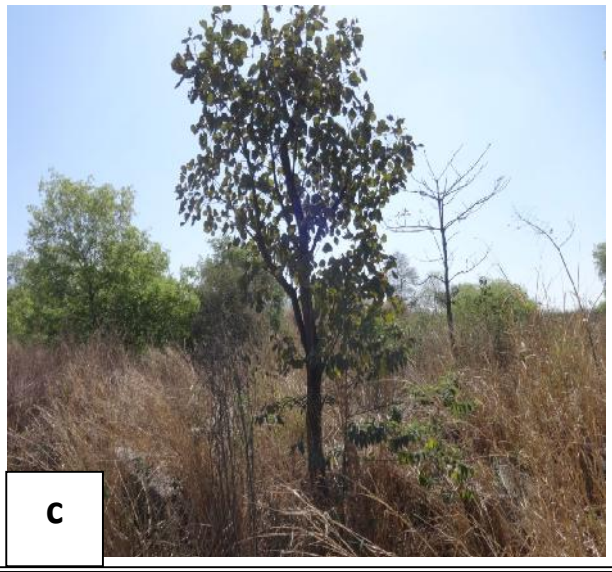

Photo 4: (a) Growth of bamboo in the restored dump, (b) Growth of old Shisam tree, and (c) Reminiscent of old Palash (*Butea monosperma*) tree in the dump.

Photo 5: photograph showing different heights of shisham (*D. sissoo*) trees growing on the dump. Background shows there are other tree species were also growing.

Photo 6: Photograph showing dry undershrubs and grasses seen in the ecorestoration site at Tetulmari. They are perennial and seen dried during onset of summer. These dry grasses will be decomposed during monsoon and will contribute to increase in soil organic carbon and nutrient content.

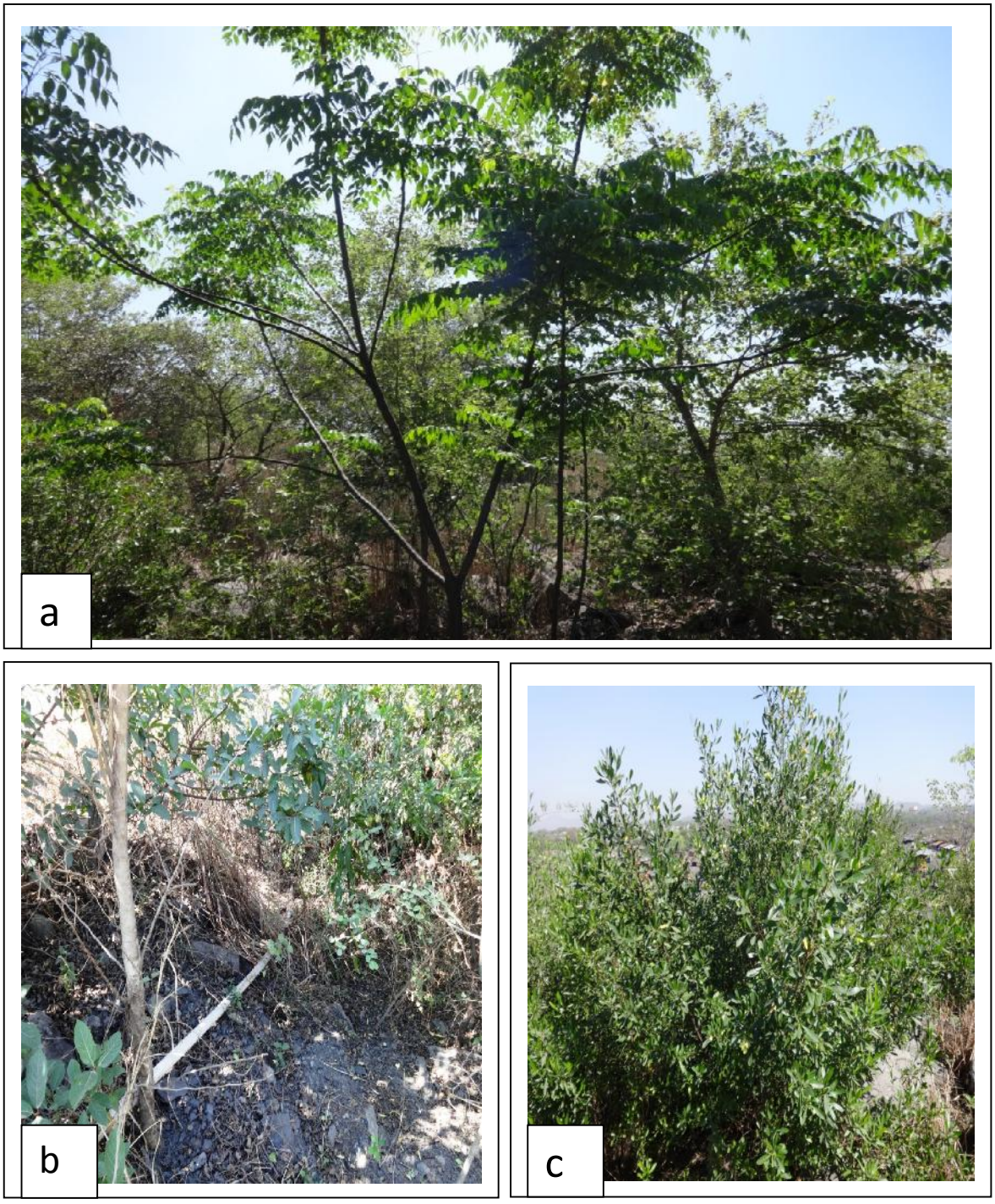

Photo 7: (a) Growth few of Bakain tree (*Melia azedarach*) was observed in the Tetulmari ecorestoration site, (b). In some places growth of Pakur (*Ficus infectoria*) also noticed. Accumulation of very few litters was observed beneath of tree species. (c) Growth of Hopbush (Vilayti mehendi) (*Dodonaea viscosa*), a evergreen, sturdy shrub also observed in the dump.

Photo 8: (a-b) Close view of the dry mulch of grasses in the restored site. (c) Showing collection of litter fall by quadrate of 50 cm x 50 cm. Minesoil samples are collected after removal of litter. (d) An uprooted dry Deenanath grass showing roots and shoot portion, used for calculation of distribution of root (15%) and shoot biomass (85%) distribution.

2.2 Damoda old Ghutway ecorestoration site 1, Barora area.

The study area of ecologically restored sites at Damoda colliery, Jharia Coalfield (JCF) is situated in the Dhanbad district of Jharkhand, Eastern India. Damoda old Ghutway Ecorestoration site 1 is a backfilled dump site of 4 ha area. Damoda site1 extends in the North south direction from 23º46´47.80´´N 86º09´58.24´´E to 23º46´45.17´´N 86º09´55.16´´E, and in the east –west direction extends from 23º46´48.19´´N 86º09´55.95´´E to 23º46´46.24´´N 86º09´57.88´´E (**Figure 2)**

The ecologically restored overburden dump at Damoda site 1 was visited two times, once before the onset of summer (12.03.2015) when soil samples and litter were collected and second time during monsoon season (25.07.15) when quadrat sampling was done for the assessment of biodiversity. The site was well protected by a boundary wall made of stones and boulders to protect the vegetation from cattle. A cemented signboard showing the type and no. of species planted is placed near the boundary wall. It also shows that at the initial stage, 19 types of plant species were planted, out of which Bamboo, Kala siris (*Abizzia lebbek*), Safed Siris (*A. procera*) and Shisham (*Dalbergia sishoo*) were dominating species (**Photo 9a, b**). During the onset of summer season (12.3.2015), litter fall was observed consisting of bamboo leaves and dry vegetation (Putus, Bantulsi etc). During the monsoon season, vegetation growth was observed satisfactory and the area was covered with greenery.

Bamboo was dominant vegetation in the Damoda-1 site (as shown in **Photo 10**a) and growing along with the boundary wall and dense growth of bamboo with other species (Siris) was observed during monsoon (25.7.2015) (**Photo 10b**).

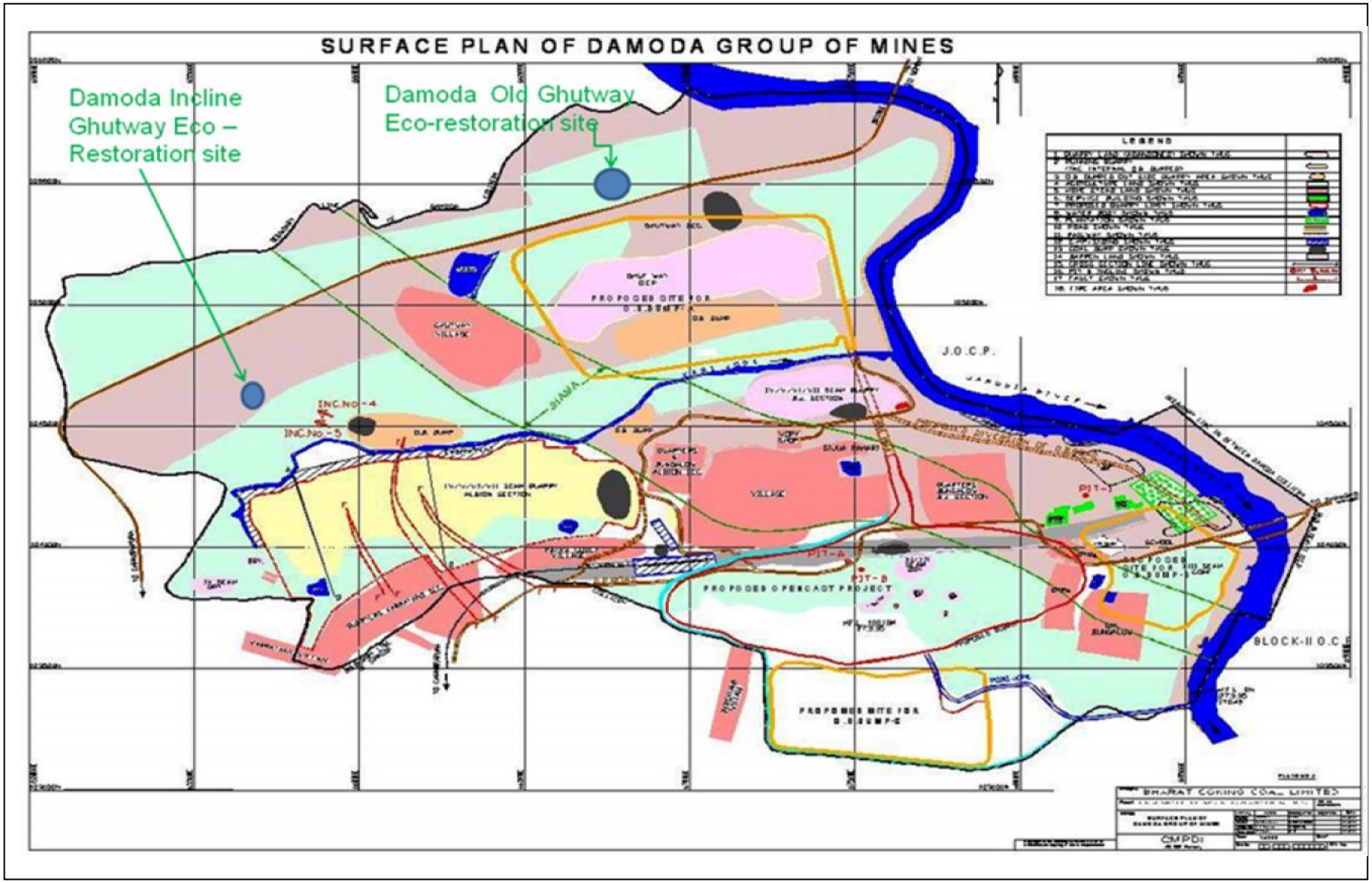

Figure 2: Site map of Damoda Old Ghutway Ecorestoration site and Damoda Inclined Ghutway Ecorestoration site.

Photo 9: Ecological restoration project site of Damoda -1, showing boundary wall and sign board indicating types of species planted and their nos (a) Photo taken on 12.3.2015 & (b) 25.7.2015 (at the initial stage 19 nos of plants were planted. Bamboo, Kala siris (*Abizzia lebbeck*), Safed Siris (*A. procera*) and Shisham (*Dalbergia sissoo*) were dominating species.

Photo 10: (a) showing boundary wall along with growth of bamboo (Photo taken: 12.3.2015). (b) Photograph of the same location taken during monsoon (25.7.2015) showing dense growth of bamboo and other species (Siris).

The ecologically restored site has dense tree growth along with undergrowth of dried up grass vegetation also. **Photo 11** shows growth of Kash (*Saccharam munja*) along with saplings of other trees, shrubs and grasses. As discussed before, quadrate sampling was done on 25. 07.2015, **Photo 12** shows the portion of sampling area (quadrat) along with the rope used for laying down the quadrat to study the vegetation density. It also shows *Albizzia lebbek* (kala siris), bamboo and accumulation of litter at the floor. The ecologically restored site has dense tree growth along with undergrowth of grasses. Close view of the Damoda-1 ecorestoration site showing satisfactory vegetation growth. Additional soil is applied in the plantation pits to ameliorate the rhizospheric temperature (**Photo 13**). **Photo-14** shows close of view of sampling quadrate (50 cm x 50 cm) taken within the sampling plot (10 m x 10 m) and observed dried up mulch of Eupatorium and other shrubs. Litter accumulation under bamboo plantation was collected by using a quadrate (50 cm x 50 cm frame, yellow colour).

Amelioration of habitat due to ecorestoration attracts colonization of fauna and reinstates food chain, like large snake (Indian Python, *Python molurus*) started migrating to this site; migration of avifauna as evident by fathers and eggs also seen, colonization of locust (grasshopper), chameleon (Lizard), different types of bird seen at the site. An artificial water storage pool was constructed at the site to attract fauna (**Photo 15 a-f**).

Photo 11: View of Damoda-1 dump at the onset of summer (12.3.2015), showing growth of Kash (*Saccharam munja*) and saplings of other trees, shrubs and grasses.

Photo 12: Portion of sampling area in the dump-1 showing *Albizzia lebbek* (kala siris), Bamboo and accumulation of litter at the floor.

Photo 13: Close view of the Damoda-1 ecorestoration site showing satisfactory vegetation growth. Additional soil is applied in the plantation pits to ameliorate the rhizospheric temperature. (Photo courtesy: BCCL)

Photo-14: Close of view of sampling quadrate (50 cm x 50 cm) taken within the sampling plot (10 m x 10 m). Observed dried mulch of *Eupatorium* and other shrubs.

Photo 15: Amelioration of habitat due to ecorestoration attracts colonization of fauna and reinstates food chain, (a) an Indian Python (*Python molurus*) started migrating to this site, (b) migration of avifauna as evident by fathers and eggs, (c) artificial water storage pool constructed at the site, (d) a colourful locust grasshopper), (e) a chameleon (Lizard) seen at the site, (f) flock of birds resting on the tree branches. (Photo courtesy: BCCL)

2.3 Damoda inclined Ghutway ecorestoration site -2, Barora area.

Damoda inclined Ghutway ecorestoration site 2 is an elevated dump site of 3 ha area located near the closed inclined Ghutway colliery area. The site plan of Damoda site 2 is given in **Figure 2.** Damoda site 2 extends in the North south direction from 23º46´22.07´´N 86º09´24.47´´E to 23º46´19.55´´N 86º09´23.09´´E, and in the east –west direction extends from 23º46´19.89´´N 86º09´25.79´´E to 23º46´22.31´´N 86º09´21.45´´E.

The ecorestoration overburden dump at Damoda site 2 was also visited two times, once before the onset of summer (12.03.2015) when soil samples and litter were collected and second time during monsoon season (25.07.15) when quadrat sampling was done for the assessment of biodiversity. The site is well protected by a boundary wall made of stones and boulders to protect the vegetation from cattle and also provided with a proper entrance gate to climb towards the dump. **Photo 16 (a)** shows a distant view of Damoda-2 site during the onset of summer. It shows the stony boundary wall along with growth of Bamboo and Palash. During monsoon season, the site shows dense and satisfactory growth of Bamboo and other species (Siris) **(Photo 16 b).**

A pavement is laid down by bricks to walk inside the site easily, which is not visible clearly due to being covered up with different types of grass vegetation (mainly *C. ciliaris* and *C. setigerus*) and other shrubs**.** Quadrat sampling at the Damoda site 2 was done for the assessment of biodiversity by laying down 2 quadrates of 10m x 10m. It shows small saplings of *D. sissoo, Albizia lebbeck* (kala siris) dominated with profuse growth of *C. ciliaris and C. setigerus* grass vegetation **(Photo 17, 18).**

It shows small saplings of *D. sissoo*, *Albizia lebbeck* (kala siris) dominated with profuse growth of *C. ciliaris and C. setigerus* grass. Field visit during the onset of summer showed dried up undershrub vegetation and also small tree species having only few branches. The leaves of trees contributed to the litterfall in the area during this time. **Photo 19 (a)** shows close view of dried up bamboo and different types of grass and shrub vegetation inside the dump site. During monsoon season, dense growth of dominant *C. ciliaris and C. setigerus* grass vegetation, Bamboo, *A. lebbeck* (Siris) and tree other species was observed **Photo 19 (b).**

Photo 16: (a) Distant view of Damoda-2 dump showing boundary wall along with growth of Bamboo, Palash (Photo taken: 12.3.2015). (**b)** Photograph of the same location taken during monsoon (25.7.2015) showing dense growth of Bamboo and other species (Siris).

Photo 17: View of Damoda-2 dump showing growth of *Cenchrus ciliaris* and other different types of grass species along with the tree plantations. It also shows the pavement laid down by bricks to walk inside the dump easily which is covered up with the grass vegetation.

Photo 18: Portion of sampling area studied by quadrate (10m x 10m) to study vegetation density in the same dump. It shows small saplings of *D. sissoo*, *Albizia lebbeck* (kala siris) dominated with profuse growth of *C. ciliaris and C. setigerus* grass vegetation.

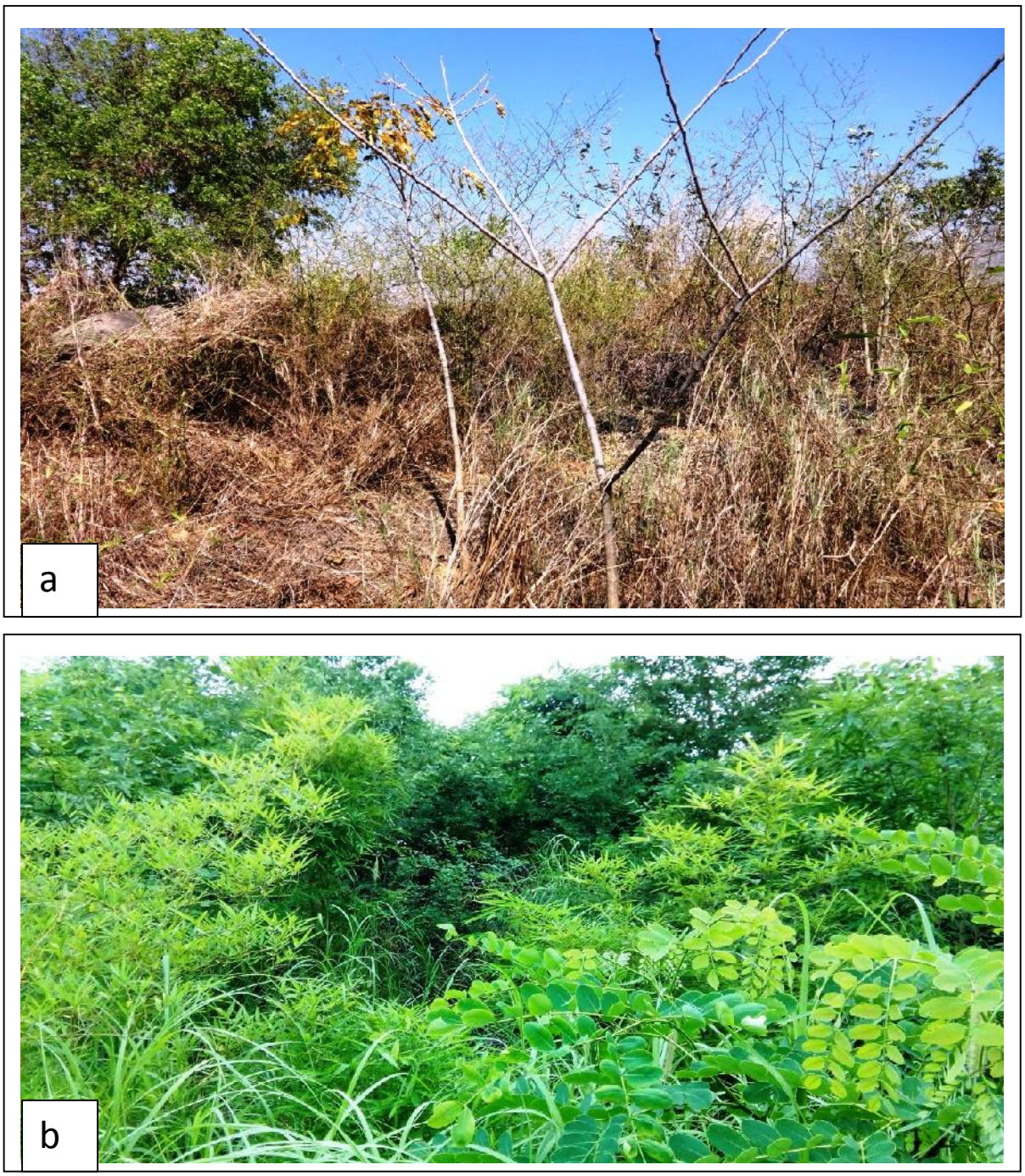

Photo 19: (a) Close view of Damoda-2 dump showing dried up bamboo and different types of grass and shrub vegetation (Photo taken: 12.3.2015). **(b)** Photograph of the same location taken during monsoon (25.7.2015) showing dense and dominant growth of *C. ciliaris and C. setigerus* grass vegetation, Bamboo, *A. lebbeck* (Siris) and other tree species.

2.4 Un-reclaimed reclaimed coal mine overburden dump at Katras area and Reference site (Reserve Forest, Damoda area).

Unreclaimed or naturally vegetated coalmine overburden dump at Katras colliery area that was selected for the study consisted of sparse vegetation. View of unreclaimed coal mine dump is shown in **Photo 20(a).** The natural colonization and predominant vegetation of the un-reclaimed reclaimed coal mine overburden dump of Katras comprised of shrubs (weeds) mainly: *Croton bonplandianus* (ban tulsi), and *Lantana Camara* and grasses such as *P. pedicellatum* (Deenanath). Reserve forest area near Damoda colliery area (located opposite the Damoda old Ghutway ecorestoration dump, on the right hand side of Hirak road) was taken as reference site (**Photo 20b**).

Photo 20: (a) View of un-reclaimed coal mine dump showing natural vegetation consisting of grasses such as Deenanath and shrubs (weeds) such as Ban tulsi, *Lantana Camera* etc. **(b)** Dense growth of 3-tier vegetation at Damoda reserve forest.

3.0 METHODOLOGY

3.1 Collection and analysis of minesoil samples

(a) Soil sampling at Tetulmari ecorestoration dump

Soil samples were collected from the selected Tetulmari ecorestoration site on 28.02.2015 and 12.03.2015. Samples were collected from the dump site by using the soil corer (15cm height). Most of the reclaimed mine soil were rocky with big boulders and it was difficult to get soil at depth of 15-30cm. Soil samples collected at random from the site using the soil corer, some of them underneath tree species after the removal of litter layer (if any) and some of the samples at other places on the top of the dump at 0-15 cm depth. Then they were properly packed in air tight sampling bags and brought carefully to laboratory for physical and chemical analysis.

Separate soil core were collected with corer (15cm height) for the measurement of bulk density at these sites. The soil samples were air dried for a week by spreading on sheets of paper. The samples were then crushed lightly by using mortar & pestle to remove the soil particles sticking to the non soil particles if any followed by sieving through a 2-mm sieve to separate the soil and non soil parts, reweighted to record the proportion of soil fraction (< 2mm size), labeled and kept in air tight sampling bags for further analysis. The description of the sampling locations underneath respective tree species according to the labelled samples was noted down.

Soil samples were collected on 28.02.2015 underneath various tree species like Shisham (*D. sissoo*), Bamboo (*Bambusa arundanacea),* Pakur (*Ficus infectoria*), Vilayti Mehendi (*Dodonea viscose*), Neem (*Azadirachta indica)* and Siris (*Albizia lebbeck*)**.** According to sampling done on 12.03.2015, total 8 no of soil samples were collected from both from the top and toe of Tetulmari ecorestoration dump at a depth of 0-15 cm and only one sample [S-1a (15-30cm)] was collected at a depth of 15-30 cm. **Table – 1** describes the soil sampling locations in detail underneath different trees or grasses at Tetulmari Ecorestoration site.

Table 1: Description of soil sampling locations at Tetulmari ecorestoration dump (Date of Soil Sampling: 12.3.2015)

Sl No	Code	Description
1	S-1 (0-15 cm)	Soil sample collected underneath various dried grasses (top of the dump) – 0-15 cm (Dump top)
1a	S-1a (15-30 cm)	Profile sampling from same location: 15-30 cm (Dump top)
2	S2 (0-15 cm)	Soil sample collected from top of the dump (close to *A indica* tree) – 0-15 cm (Dump top)
3	S-3 (0-15 cm)	Soil sample collected from top of the dump (close to *D. sissoo* tree) – 0-15 cm (Dump top)
4	S4 (0- 15 cm)	Soil sample collected below grasses (Dump top) – 0-15 cm (Dump top)
5	S5 (0-15 cm)	Soil sample collected from top of the dump – 0-15 cm (Dump top)
6	S6 (0-15 cm)	Soil sample collected underneath dry grasses (Dump top) – 0-15 cm
7	S7 (0-15 cm)	Soil sample collected from toe of the dump : 0-15 cm
8	S8 (0-15 cm)	Soil sample collected underneath dry grasses (Dump toe): 0-15 cm

(b) Soil sampling at Damoda 1 ecorestoration dump

Soil samples were collected from the selected Damoda sites 1 and 2 on 12 03 2015. Total 4 no of soil samples were collected from Damoda 1 ecorestoration site, 3 nos at a depth of 0-15 cm, with codes D-1 (0-15 cm), D-3 (0-15 cm), D-4 (0- 15 cm), whereas 1 sample with code D-2 (0-15 cm) collected at a depth of 15-30 cm underneath bamboo plantation. Description of soil sampling locations in detail underneath different trees or Bamboo at Damoda dump site- 1 is given in Table 2.

Table – 2: Description of soil sampling locations at Damoda Ecorestoration site 1 (Date of soil sampling: 12/03/15)

Sl No	Code	Description
1	D-1 (0-15 cm)	Soil sample collected underneath Bamboo plantation at the dump – 0-15 cm.
2	D-2 (0-15 cm)	Profile sampling from same location: 15-30 cm
3	D-3 (0-15 cm)	Soil sample collected below *A. lebbeck* tree at the dump – 0-15 cm.
4	D-4 (0- 15 cm)	Soil sample collected below *B. monosperma* tree (DBH 16.7 cm and height 7.5 m) – 0-15 cm after removing the litter.

(c) Soil sampling at Damoda Ecorestoration site 2

Soil samples were collected from the selected Damoda site - 2 on 12 03 2015. Total 4 no of soil samples were collected from 0-15 cm under the different tree species. Description of soil sampling locations in detail underneath different trees or Bamboo at Damoda Ecorestoration dump site 2 is given in Table 3.

Table -3: Description of soil sampling locations at Damoda ecorestoration site 2 (Date of sampling: 12.3.2015)

Sl No	**Code**	**Description**
1	D II-1 (0-15 cm)	Soil sample collected from rhizosphere of Bamboo at the dump – 0-15 cm.
2	D II -2(0-15 cm)	Soil sample collected below *Albizia spp* tree at the dump – 0-15 cm.
3	D II-3 (0-15 cm)	Soil sample collected below *Albizia spp* tree at the dump – 0-15 cm.
4	D II-4 (0- 15 cm)	Soil sample collected below *D.sissoo* tree at the dump – 0-15 cm.

(d) Collection of soil samples from unreclaimed areas and forest site

Soil sample was also collected from both natural forest site, Damoda area (undisturbed by mining) and unreclaimed site of Katras to be analyzed for comparative study.

3.2 Methods of analysis of physicochemical properties of mine soil

Following physicochemical parameters of the soil sample have been analysed:

a) The soil samples were air dried for a week by spreading on sheets of paper. The samples were then crushed lightly by using mortar & pestle to remove the soil particles sticking to the non soil particles if any followed by sieving through a 2-mm sieve to separate the soil and non soil or coarse material parts, reweighted to record the proportion of **soil fraction (<2mm size) and non soil or coarse fraction**. Percentage of coarse fraction was determined by the following formula:

Coarse fraction (%) = [Weight of coarse fractions (> 2mm size)/ (Weight of coarse fractions + dry weight of remaining soil)] x 100

The soil portion were again labeled and kept in air tight sampling bags for further analysis.

b) **Bulk density (B_d)** The soil matter contained in a unit volume of the soil sample is called its bulk density. Bulk density of soil is quite variable. It depends on the texture, structures and organic matter status of the soils. High organic matter content lowers the bulk density, whereas compaction increases the bulk density. It was determined by core method. In this method, a cylindrical metal soil corer sampler was pressed or driven into the soil to the desired depth and was carefully removed to preserve an undisturbed known volume of block of soil (soil core). Bulk volume was calculated using the core length and diameter of the cutting edge of the sampler. The sample was dried at 105ºC to 110ºC and weighed. Bulk density is the oven dried mass divided by the field volume of the sample (Maiti, 2003).

c) **Field moisture** content is generally reported as the ratio of the mass of water present in a soil sample to the mass of the sample after it has been dried to a

constant weight. It is usually a dimensionless ratio which when multiplied by 100 gives the percentage value on a mass basis. Moisture content of the collected soil samples was estimated by gravimetric method (Maiti, 2003). It is based on the principle that when moist soil is heated at 105ºC for about 24 hours, only the water which had been absorbed or held within the soil pores is evaporated.

d) The **pH** of the soil is the measure of H^+ ion activity of the soil water system, indicating whether the soil is acidic, neutral or alkaline in reaction. The pH is defined as the negative logarithm to the base 10 of the hydrogen ion activity (moles/L) in soil solution. Soil pH is normally measured in soil/water slurry in the ratio of 1:1, 1:2 or 1:2.5 (w/v). However, for reclamation point of view in this study, soil/ water ratio of 1:1 (pH paste) is recommended because it will provide close to field situation where plant roots are exposed. pH measurement at 1:2.5 (w/v) is also done by taking 20 g of soil in a 100-mL beaker and 50 mL of distilled water, stirred and then measured using pH meter.

Ions are the carrier of electricity; hence the **electrical conductivity (EC**) of the soil water system rises according to the content of soluble salts. The measurement of EC can be directly related to soluble salts concentration of the soil at any particular temperature. At normal concentration, soluble salts have little harmful effect on plant growth; however, if excessive salts exist, plant injury such as reduction of seed germination, leaf burning and death may occur (due to excessive salinity and/or exoosmotic effect). In the laboratory, EC is measured by extracting the ions in a solution from a soil sample (1:1; w/v; soil: water) using a conductivity meter (Mclean, 1982). The greater the concentration of ions or salts in the saturation extract, the higher is the EC. It is measured in mS/m or dS/m

e) **Total Soil Carbon (TSC)** is made up of living plants and animals (roots, fungi, bacteria, macro fauna and micro fauna); plant litter and all the degraded material from decomposing plant and animal material; and also the inorganic material (carbonates) Total soil carbon was determined in the CHNS elemental analyser (model: Euro EA) using CRM soil # 3 as a standard reference material after the sieving through <250 µ sieve size. The estimation of the carbon sequestration

potential through <250 µ sieve size were supported by the literature (Ussiri et al. 2014).

f) It is necessary to separate the inorganic material (which makes up 90% or more of the weight of the soil) for the correct determination of the organic matter (OM) content of soil. Thus the soil is pre-treated with 1 M HCL to remove the mineral matter. The inorganic carbonates are eliminated from the soil matrix by decomposition, since they readily react with acid leaving behind the organic C, elemental C and carbides in the sample. Thus the amount of **Soil Inorganic carbon (IC)** was determined by the difference of C between the pre acid treatment and post acid treatment soil residues using a CHNS elemental analyser.

IC (%) = TSC (%) – TSC (%) after 1 N HCL treatment

g) **Soil Organic carbon** (SOC) is contained in the soil organic fraction, which consists of cells of microorganisms, plant and animal residues at various stages of decompositions. The organic matter (humus) in the soil gets oxidized by chromic acid (potassium dichromate plus concentrated H_2SO_4) utilizing the heat of dilution of H_2SO_4. The unreacted dichromate is determined by back titration with ferrous (ammonium) sulphate (redox titration) Organic carbon was determined by this rapid dichromate oxidation technique (Walkley and Black, 1934).

h) **Available Nitrogen (N)** mineralization test gives a measure of the amount of nitrogen that may become available through microbial decomposition of the total organic nitrogen present in soils that can be uptake by plants easily. Major portion (90%) of soil nitrogen exists in combination with the organic matter. Only a negligible fraction of soil-N, which is present as inorganic form, is available to the plant. Available nitrogen or easily mineralisable nitrogen was determined by alkaline permanganate method (Subbiah and Asija, 1956)

i) **Available phosphorous (P)** was analyzed by Bray's method (Brays and Kurtz, 1966). Plants absorb inorganic P from solid or solution phase in soil. Inorganic P occurs as orthophosphate (H_2PO4 and $HPO4^{-2}$) in several forms and combinations, and only a small fraction of the total amount present may be

available to plants which are of direct relevance in assessing the phosphorus fertility level This method is based on principles that, in an acidic molybdate solution containing orthophosphate ions, a phosphomolybdate complex form that can be reduced by $SnCl_2$ and other reducing agent to a Mo blue colour. The intensity of blue colour on reduction provides a measure for the concentration of P in the test solution.

a) The term **available potassium (K)** incorporates both exchangeable and water-soluble forms of nutrients present in the soil. The readily exchangeable plus water-soluble potassium is determined in the neutral normal ammonium acetate (1N NH_4OAc) extract of soil. Exchangeable cations (K, Ca) extracted by 1 N ammonium acetate solution (w: v; 1:10) followed by flame photometer determination (Jackson, 1973). Also, Ca and Mg are essential nutrients to plants and are widely distributed and generally abundant elements in soil. Exchangeable Ca and Mg can be determined in NH_4OAc extracts of soils by titration with EDTA. Both Ca and Mg may be titrated at pH 10 using Eriochrome black T (EBT) as an indicator. Magnesium forms insoluble $Mg(OH)_2$ at pH 12 or higher if NH_4^+ salts are present, thereby allowing Ca to be titrated using Murexide or Calgon as an indicator.

b) **Cation exchange capacity (CEC)** is the maximum quantity of total cations that a soil can hold at a given pH value, available for exchange with the soil solution. CEC is used as a measure of fertility, nutrient retention capacity. The larger the CEC value, the more cations the soil can hold, and soil has good fertility. Increasing the organic matter content of soil can increase the CEC value. The CEC was determined by Na saturation method (Jackson, 1973). Increasing the organic matter content of soil can help to increase the CEC value. It is measured in milliequivalents of hydrogen per 100 g of dry soil (meq+/100g) or the SI unit expressed as (cmol+/kg).

c) **Base saturation** was calculated as the proportion of the CEC occupied by basic cations (Thomas, 1982). It is calculated as:

Base saturation %= (Bases/CEC) x 100

3.3 Ecological survey of study area

Floral Biodiversity of the ecological restored sites were assessed using standard methods. Quadrat plots were laid down with a rope randomly to get an unbiased estimation of biodiversity and health of the ecosystem. All data were carefully noted down for further calculation of few important characters of biodiversity assessment in the ecological community. Ecological survey of all the three ecorestoration study sites were conducted by identification of different tree species, counting total no of individual species present in respective quadrats. Circumference of big tree species in the quadrats were measured using measuring tape small saplings using vernier calipers for the DBH calculation. Heights of small saplings were measured with scale and big trees approximately with a measured bamboo stick. Apart from the quadrat study, some sparsely populated species growing in the ecorestoration sites which were not found in the quadrats were also identified and noted.

At Tetulmari site quadrat sampling was done during the visit on 17. 7. 2015. Nine quadrats of size 5.5m x 5.5 m (each quadrat of area 30.25 m^2), covering total area of 272.25 m^2 was laid down randomly. Same procedure was repeated for quadrat sampling at Damoda sites 1 and 2 during the visit on 25. 7. 15. Three random quadrates of size 10m x 10 m (each quadrat of 100m^2 area), covering total area of 300 m^2 was laid down at Damoda ecorestoration site 1, whereas 2 random quadrats of size 10m x 10 m (each quadrat of 100m^2 area), covering total area of 200 m^2 was laid down at Damoda ecorestoration site 2. The no of species present in each site was later expressed as no of individual species present per hectare area.

All the species diversity quadrat data noted in field is used for estimation of some of the biodiversity assessment characters such as frequency of occurrence relative density, and abundance of species of the community. Lastly, DBH of tree species measured in the quadrats can be used to calculate the total biomass and the carbon content captured within it. However, the saplings with height < 1.5 m and DBH < 3 cm and also bamboo clumps were recorded separately for calculation of their relative density.

Following parameters were calculated according to the given formula using the field generated data of quadrates for all 3 sites.

a) **Frequency %** = (Total no of quadrats in which species has occurred/Total no of quadrats studied) x 100.

b) On the basis of percent frequency values (calculated from point 1.), various species are then distributed into five **frequency classes** as follows:

Frequency %	Frequency class
0-20	A
21-40	B
41-60	C
61-80	D
81-100	E

c) **Density (individual/unit area)** = Total no of individuals of the species/Total no of quadrats studied.

d) This value is converted to Density (per hectare) using following formula:

e) **Density (per hectare)** = {Density (individual/unit area)/quadrat area} x 10000

f) **Abundance** = Total no of individuals of the species/ Total no of quadrats in which the species has occurred.

3.4 Collection and estimation of litter

Litterfall or plant litter or leaf litter is dead plant material, such as leaves, cones bark, needles seeds/nuts, logs, or reproductive organs (e.g. the stamen of flowering plants), and twigs that has fallen to the ground. Items larger than 2 cm diameter are referred to as coarse litter, while anything smaller is referred to as fine litter or litter. This detritus or dead organic material and its constituent nutrients are added to the top layer of soil, commonly known as the litter layer. Litterfall is characterized as fresh, undecomposed, and easily recognizable (by species and type) plant debris. The type of litterfall is most directly affected by ecosystem type. For example:

- In forest ecosystem, leaf tissues account for about 70% of litterfall in forests, but woody litter tends to increase with forest age (Lonsdale, 1988).
- In grasslands, there is very little aboveground perennial tissue so the annual litterfall is very low and quite nearly equal to the net primary production (Schlesinger and William, 1997).

Soil litter is classified in three layers, which form on the surface of the top layer of soil (O Horizon). These are the L, F, and H layers: L layer is the organic horizon characterized by relatively undecomposed plant material, F is the organic horizon found beneath L characterized by accumulation of partly decomposed organic matter and H is the organic horizon below F characterized by accumulation of fully decomposed organic matter mostly indiscernible.

Litterfall is a particularly key process determining the carbon and nutrient cycling of forest ecosystems, and controls the main respiration substrates on the forest floor (Roig et al., 2005). Moreover, litterfall maintains the soil fertility as it is the most important resource of soil organic matter and soil nutrients (Gairola et al., 2009). Leaf Litter on the forest floor serves as the most important sink for nutrients such as N, S and P other than carbon by decomposition process.

Environmental factors, floristic composition, stand age, tree management and stocking levels cause variations in quality and quantity of the litter (Finer, 1996). Various studies concerning litter and litter-mediated nutrient dynamics in forest ecosystems have been carried out, both in natural forests and tree plantations (Couteaux et al., 1995). Some other factors strongly infuencing litterfall are species density, basal area, altitude (Reiners and Lang, 1987), latitude (Bray and Gorham, 1964) and season (Luizao and Schubart, 1987). Swamy and Proctor (1994) have related the evergreen or deciduous nature of the constituent tree species to litter production in tropical rain forests of the Western Ghats, India.

3.4.1 Methods of Collection of litter in the present study

In the present study 8 samples of litterfall was collected at Tetulmari site (sampling on 21.7.2015) within the quadrats (5.5m x 5.5m), and also from other places at the sites randomly using a metal quadrate of 50 cm x 50cm. Litter accumulated within the metal quadrat underneath different tree species such as *D. sissoo, A. indica* and different grass litter (*P. pedicellatum, C. ciliaris, C. setigerus, S. munja, S. spontaneum, S. benghalense, C. dactylon,* etc.*)* was collected by scraping up the litter using a hand scraper. Then they were properly packed in air tight sampling bags, labeled and brought carefully to laboratory. The Ecorestoration sites were covered up with dried grass mulches by cutting them down and spreading out evenly throughout

the surface of the dump, both at barren places and areas underneath trees. Hence the litter collected underneath some of the tree species was mixed with the grass mulch.

Before taking fresh weight of collected litter, the leaves and branches were separated out from the grass portion by taking them out of the sampling bags carefully and then weighed separately This litter was then was dried in an oven at 80°C to constant weight to obtain the moisture free dry weight and the moisture content of the collected litter. In a similar manner, 5 nos of samples of litter was collected at Damoda site 1 (sampling on 25.7.2015) within the quadrats (10m x 10m) laid down, and also from other places at the sites randomly using a metal quadrate of 50cm x 50cm. Litterfall was collected under bamboo (*B. arundanacea)*, Shisham tree (*D. sissoo*) and different grasses (*P. pedicellatum*, *C. ciliaris*, *C. setigerus,* etc.*).* Three no of samples of litterfall was collected at Damoda site 2 under Palash tree (*Butea. monosperma)*, bamboo (*B. arundanacea)* and different grasses (*P. pedicellatum, C. ciliaris, C. setigerus, S. munja, C. dactylon,* etc.*)*

The dry weight of litter obtained in all the 3 ecorestoration sites was converted in kg/m^2 by dividing it with the quadrat area (i.e, 0.25 m^2) and then final litter accumulated per hectare area was calculated by multiplying the result in kg/m^2 with a factor 10 (.10,000/1000=10; 10,000 for converting m^2 to hectare and 1000 for converting kg to tons) The average values were calculated from the final results of litter accumulation of each sample. The average litter accumulated in total area of the dumps was calculated by multiplying the average litter accumulated (t/ha) by the area of the respective dump site.

3.5 Determination of above ground and below ground biomass

Biomass is defined as the total amount of live organic matter and inert organic matter (IOM) aboveground and belowground expressed in tons of dry matter per unit area (individual plant, hectare, region or country). Typically, the terms of measurement are density of biomass expressed as mass per unit area, e.g. tons per hectare.

Forest biomass is organic matter resulting from primary production through photosynthesis minus consumption through respiration and harvest (Brown, 1997). Approximately 50% of dry forest biomass comprised of carbon (Westlake, 1966), biomass

assessments also illustrate the amount of carbon that may lost or sequestered under different forest management regimes. Detailed estimations of biomass of all land cover types are necessary for carbon accounting, although very few literature are available on reliable estimations of biomass. Biomass and carbon content are generally high in tropical forests, reflecting their influence on the global carbon cycle. Tropical forests also have great potential for the mitigation of CO_2 through appropriate conservation and management (Brown, 1997). Trees often represent the greatest fraction of total biomass of a forested area, with other carbon pools only a fraction of the total tree biomass.

The Aboveground Biomass (AGB) carbon pool consists of all living vegetation above the soil, inclusive of stems, stumps, branches, bark, seeds and foliage. The most comprehensive method to establish the biomass of this carbon pool is destructive sampling, whereby vegetation is harvested, dried to a constant mass and the dry-to-wet biomass ratio established. Destructive sampling of trees, however, is both expensive and somewhat counter-productive in the context of promoting carbon sequestration. Two further approaches for estimating the biomass density of tree biomass exist and are more commonly applied. The first directly estimates biomass density through biomass regression equations. The biomass regression equations can provide estimates of biomass per tree. The data base was stratified into three main climatic zones, regardless of species: dry or where rainfall is considerably less than potential evapotranspiration (e.g. <1500 mm rain/year and a dry season of several months), moist or where rainfall approximately balances potential evapotranspiration (e.g. 1500-4000 mm rain/year and a short dry season to no dry season), and wet or where rainfall is in excess of potential evapotranspiration (e.g. >4000 mm rain/year and no dry season) The second converts wood volume estimates to biomass density using biomass expansion factors (Brown, 1997). Where stand tables – the tally of all trees in a particular diameter class are available, the biomass per average tree of each diameter class of the stand table can be estimated through biomass regression equations, also called allometric equations. Alternatively, the results of direct sampling of tree diameter in the area of interest can be used in these regression equations. The total biomass of the forest stand is then derived from the average tree biomass multiplied by the number of trees in the class, summed across all classes. In both tropical and temperate forests, such diameter measurements explain more than

95% of the variation in tree biomass (Brown et al, 1989). These 2 approaches and different equations according to rainfall regimes is described in details in Annexture 1 and 2.

The Belowground Biomass (BGB) carbon pool consists of the biomass contained within live roots. As with AGB, although less data exists, regression equations from root biomass data have been formulated which predict root biomass based on above-ground biomass carbon (Cairns et al., 1997). Cairns et al. (1997) reviewed 160 studies covering tropical, temperate and boreal forests and found a mean root-to-shoot (RS) ratio of 0.26, ranging between 0.18 and 0.30. Although roots are believed to depend on climate and soil characteristics (Brown et al, 1989, Cairns et al. 1997) found that RS ratios were constant between latitude (tropical, temperate and boreal), soil texture (fine, medium and coarse), and tree-type (angiosperm and gymnosperm).

Non-destructive (conservation) methods were also used for calculation of BGB or root biomass (RB) for similar types of vegetation and coefficients as reported in the literature. They are derived from the measurement of the aboveground biomass. Santantonio et al (1977) suggested that the biomass is close to 20 percent of the total aboveground biomass and indicate that the majority of the underground biomass of the forest is contained in the heavy roots - generally defined as those exceeding 2mm in diameter. According to MacDicken (1997), the ratio of belowground to aboveground biomass in forests is about 0.2, depending on species. A conservative estimate of root biomass in forests would not exceed 10-15 percent of the aboveground biomass.

3.5.1 Methods of determination of Aboveground and Belowground biomass in present study

In the present study, non- destructive method of estimation of AGB is used. AGB of tree species is estimated from the field measurements (DBH of tree species) at all the three ecorestoration sites (quadrat data) by using both allometric and regression equations in two ways.

a) Firstly, the DBH of individual tree species in all 3 sites was divided into DBH classes 3-5, 5-7, 7-9, 9-11, 11-13, 13-15, 15-17, 17-19 and 19-21 cm respectively. Mean DBH of trees in each diameter class of individual tree species was used to calculate the AGB accumulation, per average tree (in kg) of each diameter class

through following biomass regression equation revised from Brown et al. (1989) and proposed for dry forest in India with rainfall > 900 mm/year (Brown, 1997)

$$\mathbf{Y = \exp\{-1.996+2.32*\ln(D)\}}$$

Where, Y= aboveground biomass (kg)

D = Mean Diameter at breast height (DBH) of each tree species in each diameter class (cm)

The average AGB attained was then multiplied to the tree density per hectare in the diameter classes to convert to t/ha.

After the estimation of average AGB, following equation from the literature (MacDicken 1997) was used for estimation of BGB or RB;

Belowground Biomass (t/ha) = Average Aboveground Biomass (t/ha) × 0.2.

b) The total AGB contributed by different trees was calculated by summing the individual AGB of each species. The total RB of different tree species was estimated by summing up the average RB of each species (calculated from average AGB). .The total AGB and RB of different tree species is summed up to calculate the total biomass of trees (t/ha) for each ecorestoration site.

In this study carbon sequestration by bamboo plantation was calculated by considering the work of Singh and Singh (1999). They estimated biomass of 3 years old bamboo plantation at reclaimed Jayanta opencast coalmine overburden dumps, Singrauli, India. Since, age of reclamation is 3 yrs, same data has been considered in the present study. They reported foliage contributes 6 tons/ha, current shoot system 4.5 t/ha, rhizomes 11.9 t/ha and root system 3.6 t/ha; constituting total of 26.1 tons/ha (for green clumps density of 4000 nos/ha). This figure is in very high, therefore, in the present case only 40% is considered (which is 10.44 t/ha), because average number of shoots in the clump was about 6-7 nos; all the shoots in the clumps are very young, and shorter height.

A factor 0.0065 is derived based on Singh and Singh (1999) report, (26.1 tons/ha / 4000 nos/ha = 0.0065). Thus, the total biomass of bamboo per hectare in each ecorestoration site is calculated as:

Total biomass of bamboo (no of clumps/ha) = density of bamboo (no of clumps/ha) x 0.0065.

Then the corrected final biomass (t/ha) of bamboo plantation is calculated (based on 40% of total biomass considered) as follows:

Corrected biomass of bamboo (t/ha) = Total biomass of bamboo (no of clumps / ha) x 0.4.

Thus the total final biomass (trees and bamboo plantation) of each ecorestoration site is calculated by adding up the biomass of trees (t / ha) and corrected biomass of bamboo (t/ha).

3.6 Estimation of Carbon Sequestration

Carbon is lost to the atmosphere as CO_2. To convert carbon in biomass to CO_2, the tons of carbon are multiplied by the ratio of the molecular weight of carbon dioxide to the atomic weight of carbon (44/12 or 3.67). Estimating the biomass density of forest components is, therefore, the first step in forest carbon accounting. Carbon pools are components of the ecosystem that can either accumulate or release carbon and have classically been split into four main categories in the present study: living AGB, living BGB, dead organic matter in litter and soil organic matter.

The tree component of forest constitutes the major fraction of biomass, and so while conversion of biomass into carbon and CO_2, the understorey is often omitted from accounting. This omission results in a conservative carbon stock estimate but is justified only in areas where trees are present in high density; neglecting the shrub layer in open woodlands, savannah or in young successional forest may significantly underestimate carbon density. In the present study also, the shrub layer is omitted from accounting.

3.6.1 Methods of estimation of Carbon Sequestration in present study

In the present study, the tree species with height >1.5- 2m and DBH > 3cm were considered only for the calculation of AGB and RB and hence not used for carbon sequestration estimation .The total biomass of trees and bamboo plantation as calculated in **section 3.5.**1 is expressed in t/ha. The amount of carbon sequestered was calculated by reducing this biomass yield to its 50% as per the guidelines of IPCC, 2006. Hence biomass value was converted to carbon stocks by multiplying a factor 0.5 (IPCC, 2006) and it was expressed in tons per hectare. Biomass carbon

was then multiplied by 44/12 ratio (factor 3.67) in order to convert the carbon to tons of CO_2 sequestered per hectare.

C sequestered from litter accumulation was determined by multiplying a factor 0.4 with the average litter accumulated in t/ha (described in section 3.4.1), assuming 40% carbon present in the litter. Then it was multiplied by 44/12 ratio (factor 3.67) in order to convert the carbon to CO_2 sequestered. Final C sequestered value in the total site can be obtained by multiplying with the area of the dump site (value obtained in tons). Carbon sequestration rate can be calculated by dividing the C sequestered (t/ha) with the approximate age of the dump.

SOM includes carbon in both mineral and organic soils and is a major reserve of terrestrial carbon (Lal and Bruce, 1999). Inorganic forms of carbon are also found in soil: however, forest management has greater impact on organic carbon and so inorganic carbon impact is largely unaccounted. C sequestered from soil organic carbon was calculated using the following equation by Lal et al. (1998)

$$\textbf{Mg C ha}^{-1} = [\%C * \text{Corrected } B_d * d\ (m) * 10^4\ m^2\ ha^{-1}] / 100$$

Where, Mg C ha^{-1} = Mega grams C per hectare (1 M =10^6),

B_d (Mg m^{-3}) = corrected soil bulk density (Mega gram per cubic meter),

d = soil depth (m),

In the present study,

% C = biogenic carbon (total soil carbon free of inorganic carbon and coal carbon).

Total soil C (TSC) content in reclaimed or biologically restored minesoils consist of three types of pools namely (**Fig. 3**) (i) soil inorganic C (SIC), (ii) geogenic C (coal-C or fossil C) and (iii) biogenic C (plant derived recent SOC) (Ussiri and Lal, 2008). Sources of SIC are parent rock of overburden materials which consists of carbonates or calcite and dolomite in significant concentrations ”Geogenic C” in minesoils originates from the incorporation of coal particles or coal dust during overburden removal, coal mining and reclamation operations while “biogenic C” originates from recent biological inputs. Microbial decomposition of biogenic C sources (litter) along with different pedogenic process leads to their mixing with geogenic C and also the humus fraction. The stable fractions of ”biogenic C” such as the humus and mineralizable

fractions are responsible for maintaining long term CO_2 sequestration as it controls the SOC pool. However, standard procedures for quantifying SOC concentrations in reclaimed minesoils such as the chemical wet oxidation (Walkley and Black 1934) or dry combustion methods (LOI) cannot distinguish coal C from biogenic C in RMS due to presence of higher amount of coal carbon. This leads to overestimation of C pools and sequestration rates (Ussiri et al. 2014)

In Indian conditions of biological reclamation or ecorestoration of coal mines, higher coal carbon percentage are found apart from the biogenic C derived from plant biomass in due to lack of proper reclamation techniques. Also, inorganic carbon (IC) is present in considerable quantities due to the parent rock materials as discussed. Hence in the present study, IC % was determined as discussed in **section 3.2 (f)** by HCL treatment of the minesoil. The coal C % was then estimated by method described by Ussiri et al., 2014. This coal C % and IC % value is then substracted from the total soil carbon (TSC) value (calculated by CHNS analyzer; section 3.2 (e)) to get the biogenic C% (used for the calculation of C sequestration from soil) using the following formula:

%C (biogenic carbon) = Total soil carbon (TSC)% -(coal carbon % + inorganic carbon (IC) %)

Corrected Bulk Density of soil samples used in the equation was determined after removal of non soil or coarse fraction (>2mm sieve size).

A factor of 3.67 is multiplied with the carbon sequestered from minesoil (t C/ha) to express finally as tons of carbon dioxide sequestered or captured per hectare (t CO_2/ha).

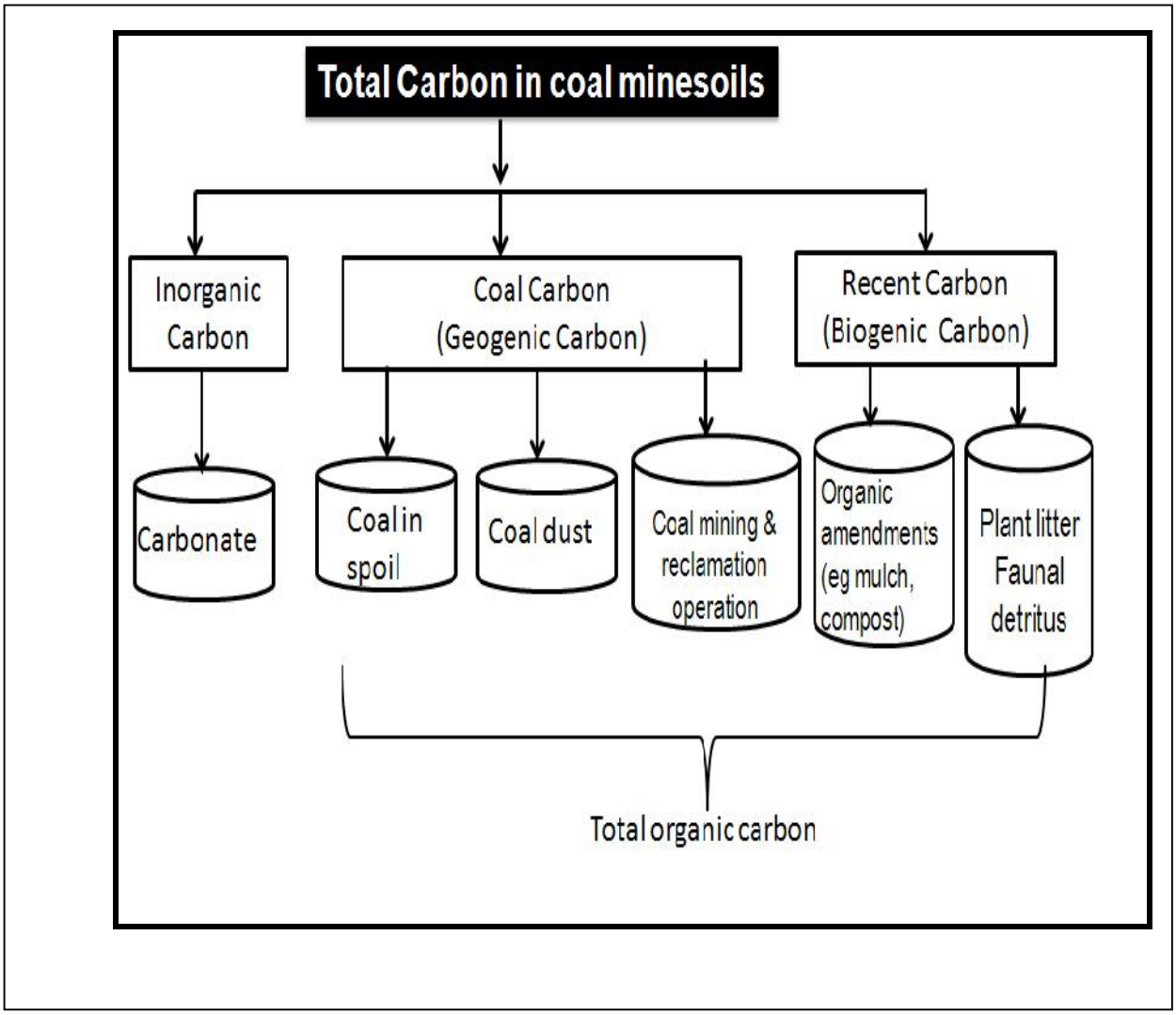

Figure 3: Sources of total carbon in reclaimed coalmine soils

3.7 Methods of estimation of Total CO_2 Sequestration in present study

In RMS, there are three potential C sequestration pools, mainly: (i) above and below ground biomass, (ii) litter layer, and (iii) soil organic matter (SOM). Terrestrial plants can sequester carbon through photosynthesis which is stored in various aboveground (leaf, coarse woody material, branch, and logs) and belowground (live and dead roots, and SOM) biomass. This carbon is then transformed from live to dead organic matter by decomposition via microbes.

Vogt et al. (1995) stated that living biomass constitute 40 to 62% of total ecosystem carbon, whereas SOM constitute 33 to 50% of Carbon (C) in a forest. Different tree species have different degree of influence on C pool in a reclaimed mine soil (RMS) due to variation in characteristics of aboveground and belowground biomass.

Thus, in this present study, the C pool of all 3 ecorestoration sites, Tetulmari, Damoda site 1 and Damoda site 2 can be assessed by adding following components of C pool of the ecosystem (Shrestha and Lal, 2010):

a) SOC at 0 to 15 cm depth **($C\ Pool_{soil\ 0\text{-}15\ cm}$)**

b) Sum of Aboveground (AG) and Belowground or root (BG) biomass (bio) carbon **($CPool_{bio\ (AG+BG)}$)**

c) Litter biomass carbon **($C\ Pool_{litter}$)**

$$Eco\ C\ Pool = C\ Pool_{bio\ (AG+BG)} + C\ Pool_{litter} + C\ Pool_{soil(0to15\ cm)}$$

Where, **Eco C Pool** = total ecosystem C pool;

Total carbon dioxide sequestered by the ecorestoration sites, unreclaimed site and the natural reference forest site is determined by the following formula:

Total CO_2 sequestered (t CO_2 / ha) = CO_2 sequestered $_{(AG+BG)}$ + CO_2 sequestered $_{(litter)}$ + CO_2 sequestered $_{(soil;\ 0\text{-}15\ cm)}$

4.0 RESULTS AND DISCUSSION

4.1 Tetulmari ecorestoration site

4.1.1 Determination of Density and Relative Density of plant species

Nine quadrats of 5.5 m x 5.5.m were laid down in the ecorestoration site to count the number of total species of the area. In nine quadrats (equal to 272.25 m^2), 53 nos of trees were recorded, where *Dalbergia sissoo* constitutes 66% of total population (**Fig 4a &b**). The tree density was calculated as 1947/ha and total nos of trees in 8 ha of dump were estimated as 15,576 nos. The details of density of tree/ha and total estimated tree count, frequency, frequency class, abundance and density of individual tree/ha are given in **Table 4a.**

During the field survey, a large number of saplings of less than 1.5 m heights were found, which are not consider for biomass estimation and carbon sequestration study. During the quadrate sampling, a total of 37 saplings of <1.5m height were noted in 272.25 m^2 area (**Table 4b**). The no of saplings found in each quadrat varied from 1 to 13 nos. Total 8 tree species and bamboo was considered for the CS study whereas 9 sapling species found in the quadrat was not considered for the CS study. Among these saplings, highest density was contributed by *D. sissoo* 30% of density, followed by *A. indica* 14% and *Syzizium cumini* 16% and rest contributed by other species Total nos of saplings were estimated as 1359/ha, therefore, in 8ha, total saplings calculated as 10,872 nos. Only in one quadrat, 4 nos of bamboo clumps were observed. Therefore the density of bamboo clumps was calculated as 147 clumps/ha; total clumps in 8 ha area of the dump was 1176 nos. A total of 33 nos of species were observed in the site by the field survey, out of which only 10 nos species were present in the quadrate including both big trees saplings of height <2 m and grass species. All types of vegetation of the Tetulmari ecorestoration site is given in **Table 5**.

4.1.2 Measurement of Diameter at Breast Height (DBH) of tree species

Diameter at Breast Height (DBH) of tree species were measured for the estimation of above ground biomass (ABG) and root biomass (RB) of tree species by using allometric equation, which is discussed in the section 3.3. DBH of all the 53 trees were measured by using Vernier caliper and measuring tape. A detail of measurement of DBH of all the individual tree species is given in **Table 6**

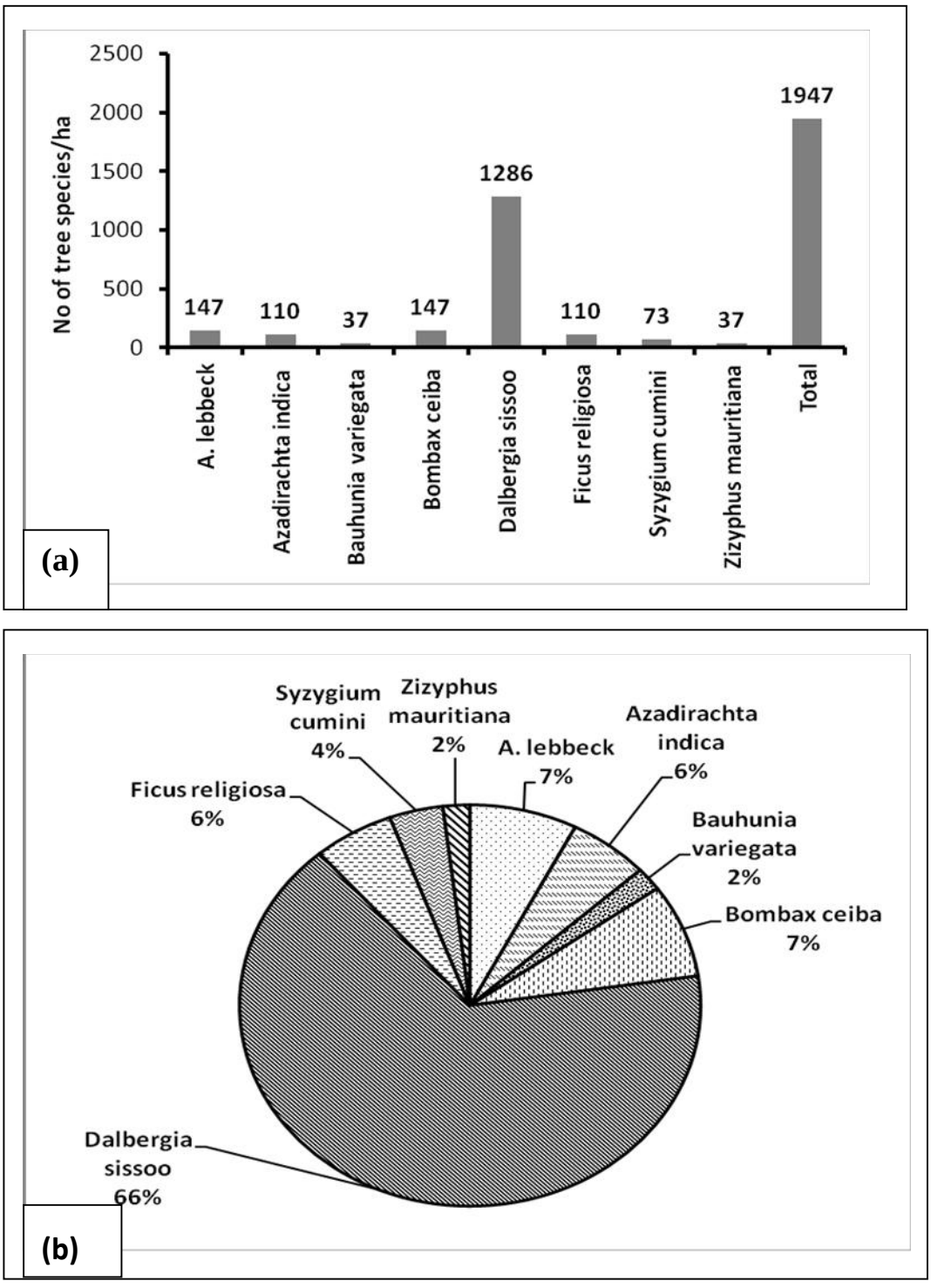

Figure 4 (a&b): Relative distribution of tree species in the Tetulmari ecorestoration site

Table 4 (a): List of species recorded in quadrate of **Tetulmari ecorestoration site**, showing frequency (%), density (trees/ha), relative density and abundance. (Size of quadrat in this study: 5.5m x 5.5m=30.25m^2) (Date of sampling: 17.7.2015)

Sl no	Name of sp	Quadrats laid down									Total no of individual sp.	Total no of quadrats of occurrence	Total no of quadrats studied	Frequency (%)	Frequency class	Density (individual/unit area)	Density(per hectare)	Abundance	% of the total no of species
		1	2	3	4	5	6	7	8	9									
1	*Albizia lebbeck*	-	-	2	-	-	-	-	-	2	4	2	9	22.22	B	0.44	147	2	8
2	*Azadirachta indica*	1	1	-	-	-	-	-	1-	-	3	3	9	33.33	B	0.33	110	1	6
3	*Bauhunia variegata*	-	-	1	-	-	-	-	-	-	1	1	9	11.11	A	0.11	37	1	2
4	*Bombax ceiba*	-	-	-	-	3	-	-	1	-	4	2	9	22.22	B	0.44	147	2	8
5	*Dalbergia sissoo*	4	2	6	-	7	3	4	6	3	35	8	9	88.89	E	3.89	1286	4.4	66
6	*Ficus religiosa*	-	2	-	-	-	-	1	-	-	3	2	9	22.22	B	0.33	110	1.5	6
7	*Syzygium cumini*	-	-	-	-	-	-	-	2	-	2	1	9	11.11	A	0.22	73	2	4
8	*Zizyphus mauritiana*	-	-	-	-	-	-	-	1	-	1	1	9	11.11	A	0.11	37	1	2
	Total=	5	5	9	0	10	3	5	11	5	**53**						**1947**		

No of trees in 272.25 m^2 = **53 nos**

No of trees in 1 ha = (53/272.25)*10000 = **1947 trees/ha.**

Total trees in 8 ha Tetulmari Ecologically Restored dump = 1947 nos/ ha x 8 ha= **15,576 nos.**

Table 4 (b): List of saplings of height <1.5 m and Bamboo clumps observed in the quadrate of Tetulmari ecorestoration site. (Size of quadrat in this study: 5.5m x 5.5m=30.25m^2)

Sl no.	Tree species	Quadrates laid down									Total no of saplings	Relative density (%)
		1	2	3	4	5	6	7	8	9		
1	*Albizia lebbeck*	1		2	1	-	-	-	-	-	4	11
2	*Azadirachta indica*	-	4	-	1	-	-	-	-	-	5	14
3	*Bauhunia variegata*	-	1	1	1	-	-	-	-	-	3	8
4*	***Bambusa arundanacea* (clumps)**	-	-	-	-	-	**4**	-	-	-	-	**0**
5	*Dalbergia sissoo*	-	4	2	2	-	2	1	-	-	11	30
6	*Phyllanthus emblica*	1	1	-	3	-	-	-	-	-	5	14
7	*Pongamia pinnata*	1	-	-	-	-	-	-	-	-	1	3
8	*Psidium guajava*	1	-	-	-	-	-	-	-	-	1	3
9	*Syzygium cumini*	-	-	-	5	-	-	-	1	-	6	16
10	*Terminalia arjuna*	1	-	-	-	-	-	-	-	-	1	3
	Total=	5	10	5	13	0	2	1	1	0	**37**	

* Bamboo clumps-4; Total area of 9 quadrate = 30.25 m^2 x 9 = 272.25 m^2.

No of saplings (<1.5 m) in 272.25 m^2 = 37 nos (excluding 4 nos bamboo clumps)

No of saplings /ha = (37/272.25)*10000 =1359 nos

No of bamboo clumps /ha = (4/272.25)*10000 = 147 nos

So, Density of plantation in 8ha

a) Saplings = 1359 saplings/ ha x 8 ha = **10, 872 nos of saplings**.
b) Bamboos = 147 nos. of bamboo/ha x 8 ha = **1176 no of clumps.**

Table 5: Type of vegetation in Tetulmari ecorestoration site

Sl no.	Type of plantation	Common name	Botanical name	Family
1	**Trees**	Sisham (Sissoo)	*Dalbergia sissoo*	Fabaceae
2		Neem (Margosa tree)	*Azadirachta indica*	Meliaceae
3		Bakain (Ghora neem)	*Melia azedarach*	Meliaceae
4		Gular, Dumar (Cluster Fig Tree**)**	*Ficus racemosa*	Moraceae
5		Pakar (Pakur)	*Ficus infectoria*	Moraceae
6		Karanj (Indian Beech)	*Pongamia pinnata*	Fabaceae
7		Kachnar (Kanchan)	*Bauhinia variegata*	Fabaceae
8		Radhachura (The Copper Pod)	*Peltophorum pterocarpum*	Fabaceae
9		Kala Siris	*Albizia lebbeck*	Fabaceae
10		White Siris	*Albizia procera*	Fabaceae
11		Palash (Flame of the forest)	*Butea monosperma*	Fabaceae
12		Chatim (Indian devil tree)	*Alstonia scholaris*	Apocynaceae
13		Amla (Indian gooseberry)	*Phyllanthus emblica*	Phyllanthaceae
14		Semul (silk cotton tree)	*Bombax ceiba*	Malvaceae
15		Arjun	*Terminalia arjuna*	Combretaceae
16		Gamhar (White teak)	*Gmelina arborea*	Lamiaceae
17		Peepal (ashwattha tree)	*Ficus religiosa*	Moraceae
18		Charcoal tree	*Trema orientalis*	Cannabaceae
19	**Grasses**	Dennanath	*Pennisetum pedicellatum*	Poaceae
20		Kans	*Saccharam benghalense*	Poaceae
21		Kans	*Saccharam spontaneum*	Poaceae
22		Kash	*Saccharam munja*	Poaceae
23		Sui ghas	*Cenchrus ciliaris*	Poaceae
24		Dhaman grass	*Cenchrus setigerus*	Poaceae
25		Bamboo (Indian thorny bamboo)	*Bambusa arundanacea*	Poaceae
26		Doob grass	*Cynodon dactylon*	Poaceae
27	**Shrubs**	Nirgundi	*Vitex* negundo	Lamiaceae
28		Ber (Indian plum)	*Ziziphus mauritiana*	Rhamnaceae
29		Hopbush (vilayti mehandi)	*Dodonaea viscose*	Sapindaceae
30	**Fruit trees**	Jamun	*Syzygium cumini*	Myrtaceae
31		Mango	*Mangifera indica*	Anacardiaceae
32		Guava	*Psidium guajava*	Myrtaceae
33		Kathal	*Artocarous heterophyllus*	Moraceae

Table 6: Classification of tree species based on DBH at Tetulmari ecorestoration site.

Name of Tree species	Occurrence of trees in Quadrat no.	Circumference (cm)	DBH(cm)**	No of trees in each quadrat (n)
A. lebbeck (N= 4)*	3	14	4.46	2
		10	3.18	
	9	18	5.73	2
		13	4.14	
Azadirachta indica (N=3)	1	10	3.18	1
	2	29	9.24	1
	8	36	11.46	1
Bauhunia variegate (N=1)	3	10	3.18	1
Bombax ceiba (N=4)	5	18	5.73	3
		35	11.15	
		19	6.05	
	8	36	11.46	1
Dalbergia sissoo (N= 35)	1	18	5.73	4
		15	4.78	
		38	12.10	
		15	4.78	
	2	11	3.50	2
		14	4.46	
	3	29	9.24	6
		14	4.46	
		32	10.19	
		11	3.50	
		13	4.14	
		10	3.18	

Name of Tree species	Occurrence of species in Quadrat no.	Circumference (cm)	DBH(cm)**	No of trees in each quadrat (n)
	5	40	12.74	7
		41	13.06	
		42.5	13.54	
		25	7.96	
		35	11.15	
		42	13.38	
		38	12.10	
	6	18	5.73	3
		29	9.24	
		11	3.50	
	7	34	10.83	4
		29	9.24	
		58	18.47	
		47	14.97	
	8	53	16.88	6
		29	9.24	
		18	5.73	
		24	7.64	
		63	20.06	
		65	20.70	
	9	65	20.70	3
		61	19.43	
		43	13.69	
Ficus religiosa (N=3)	2	11	3.50	2
		10	3.18	
	7	31	9.87	1
Syzygium cumini (N=2)	8	16	5.10	2
		13	4.14	
Zizyphus mauritiana (N=1)	8	28	8.92	1
			Total	53

*N=Total no of tree species present; **DBH (cm) = circumference (cm) / 3.14

4.1.3 Estimation of above ground biomass (AGB) and Root biomass (RB) and CO_2 sequestration.

Estimation of above ground biomass (AGB) and root biomass at Tetulmari site based on DBH classes of individual tree species are given in **Table 7.** Density of tree species used for CS study at the Tetulmari site was 1947 nos/ ha. Both above ground (AGB) and below ground biomass (BGB) for 8 species were calculated by using allometric equations. Out of 8 species, *D. sissoo* has contributed maximum biomass, (classified in 9 DBH classes ranging from 3-5 cm, to 19-21 cm). Among all these 9 DBH classes, a total of 1286 nos of Shisham tree/ ha was calculated. At the higher DBH class, both AGB and BGB increased in exponential manner (Annexure -1).
In **Table 8**, estimation of total above ground biomass (AGB) and below ground biomass (BGB) or root biomass was done by the most commonly used allometric equations as follows:

1. **Brown (1997)**, also used in the FAO (1997) for AGB calculation. (Details of Brown 1997 equation as published in FAO web site given in **Annexure -2**).
2. **MacDicken (1997)** used for estimation of BGB or RB:

In this study carbon sequestration by bamboo plantation was calculated by considering the work of Singh and Singh (1999). Details of calculation of biomass of bamboo plantation and CO_2 sequestration from total biomass (tree + bamboo) is given in **section 3.5.1**.

The total tree biomass was estimated 77.08 t/ha (by using Brown equation, 1997) and the corrected biomass of bamboo clumps was calculated as 0.387 t/ha.

Thus the total biomass was calculated as 77.46 t/ha.

The carbon stock of the tree and bamboo biomass of 77.46 t/ha is equal to 38.73 t/ha (a factor of 0.5 is multiplied to convert the amount of carbon fixed in the biomass). The conversion factor of 0.5 is taken from FAO (1997).

Next, the amount of CO_2 sequestered per hectare was calculated as 142.14 t of CO_2/ha.

The CO_2 sequestered by the tree and bamboo biomass in 8 ha site of Tetulmari area was calculated as 1137.12 tons.

The rate of CO_2 sequestration was calculated as 47.38 tons CO_2 /ha/yr.

Table 7: Estimation of above ground biomass (AGB) and root biomass (RB) based on DBH (Diameter at Breast height) classes for individual tree species (no of trees/ha = 1947)

Tree species name	DBH range (cm)	Avg DBH (cm)	AGB of individual tree (kg)[1]	No of trees in 272.25 m^2	No of trees/ha[3]	AGB of trees (t/ha)	Root biomass (RB) (t/ha)[2]
A. lebbeck	3 - 5	3.93	3.25*****	3	110**	0.356#	0.07##
	5 - 7	5.73	7.81	1	37	0.29	0.06
	Total		**11.06**	**4**	**147**	**0.64**	**0.13**
Azadirachta indica	3 - 5	3.18	2.00	1	37	0.07	0.01
	9 - 11	9.24	23.61	1	37	0.87	0.17
	11- 13	11.46	38.98	1	37	1.43	0.29
	Total		**64.59**	**3**	**110**	**2.37**	**0.47**
Bauhunia variegata	3 - 5	3.18	2.00	1	37	0.07	0.01
	Total		**2.00**	**1**	**37**	**0.07**	**0.01**
Bombax ceiba	5 - 7	5.89	8.32	2	73	0.61	0.12
	11- 13	11.31	37.74	2	73	2.77	0.55
	Total		**46.06**	**4**	**147**	**3.38**	**0.68**
D. sissoo	3 - 5	4.03	3.46	9	331	1.14	0.23
	5 - 7	5.73	7.80	3	110	0.86	0.17
	7 - 9	7.80	15.96	2	73	1.17	0.23
	9 - 11	9.66	26.20	6	220	5.77	1.15
	11- 13	12.02	43.52	4	147	6.39	1.28
	13 - 15	13.73	59.19	5	184	10.87	2.17

	15 -17	16.88	95.63	1	37	3.51	0.70
	17-19	18.47	117.88	1	37	4.33	0.87
	19-21	20.22	145.45	4	147	21.37	4.27
	Total		**515.09**	**35**	**1286**	**55.43**	**11.09**
Ficus religiosa	3 - 5	3.34	2.24	2	73	0.16	0.03
	9 - 11	9.87	27.56	1	37	1.01	0.20
	Total		**29.79**	**3**	**110**	**1.18**	**0.24**
Syzygium cumini	3 - 5	4.14	3.67	1	37	0.13	0.03
	5 - 7	5.10	5.94	1	37	0.22	0.04
	Total		**9.61**	**2**	**73**	**0.35**	**0.07**
Zizyphus mauritiana	7 - 9	8.92	21.76	1	37	0.7993	0.16
	Total		**21.76**	**1**	**37**	**0.80**	**0.16**

[1] Above ground biomass is **c**alculated by using allometric equation proposed by Brown (1997):

Y (biomass in kg) = exp (-1.996 + 2.32 * ln DBH (cm));

***** exp (-1.996 +2.32 * ln (3.93)) = **3.25 kg**

[2] Root biomass is calculated by MacDicken (1997) formula:

Root biomass = above ground biomass (t/ha) x 0.2

[##] 0.356 (t/ha) x 0.2 = 0.07 (t/ha)

[3]No of trees/ ha is calculated by =

= (No. of trees in total quadrate / area of quadrate, 272.25 m2) x 10,000 (to convert m^2 to ha)

****** (3/272.25) x 10000 = 110 no of trees / ha

[#] Conversion of AGB of trees from kg to t/ha

3.25 kg x 110 (no of trees/ha) x 10^{-3} (conversion factor of biomass; kg to tons)
= 0.356 tons/ha.

Table 8: Estimation of total above ground biomass (AGB) and root biomass (RB) of tree and bamboo [using Brown (1997), MacDicken (1997) equation] and CO_2 sequestration at Tetulmari ecorestoration site

Tree species name	No of trees/ ha	Total AGB of tree species (t/ha)[1]	Total RB of tree species (t/ha)[2]	**Total biomass (AGB+RB) (t/ha)**
	a	b	c	d = (b +c)
A. lebbeck	147	0.64	0.13	0.77
Azadirachta indica	110	2.37	0.47	2.85
Bauhunia variegata	37	0.07	0.01	0.09
Bombax ceiba	147	3.38	0.68	4.06
Dalbergia sissoo	1286	55.43	11.09	66.51
Ficus religiosa	110	1.18	0.24	1.41
Syzygium cumini	73	0.35	0.07	0.42
Zizyphus mauritiana	37	0.80	0.16	0.96
Total	1947	64.23	12.85	**77.08**

[*] All the values in column a, b and c obtained from **Table 7**

[1] Values calculated by Brown (1997) equation;

[2] Values calculated by MacDicken (1997) formula

Total tree biomass (above ground and root biomass) = **77.08 tons/ha**

Bamboo density (nos of clumps/ha)	Average biomass (t/ha)*	Corrected Biomass (tons/ha)**
147	0.956	0.382

*Average biomass (t/ha) = density of bamboo x 0.006525 = 147 bamboo shoots / ha x 0.0065 = 0.959 t/ha.

The factor 0.0065 is derived from Singh & Singh (1999) (26.1 t/ha / 4000 nos/ha = 0.0065).

Corrected Biomass (t/ha) = 40% of biomass is considered due to young age of bamboo plantation = 0.956 t/ha x 0.4 **= 0.382 tons/ha

Total biomass (tree + bamboo) plantation = 77.08 + 0.382 = **77.46 t/ha**

Total Carbon stock (trees + bamboo) = 77.46 t/ha x 0.5 (factor to convert amount of C fixed in the biomass) = **38.73 t/ha**

CO_2 sequestered = 38.73 t/ha x 3.67 (factor to convert C to CO_2) = **142.14 t/ha.**

CO_2 sequestered in the total biomass (tree + bamboo) in 8 ha dump = 142.14 t/ha x 8 ha = 1137.12 tons.
Therefore, rate of CO_2 sequestration = [1137.12 tons/8ha/3 yrs) = 47.38 tons of CO_2/ha/yr

4.1.4 Estimation of CO_2 sequestration in litter

Numerous studies have shown the significant differences in litterfall seasonal patterns within several ecosystem types and even for different tree species in the same ecosystems. Litter accumulation underneath different trees and grasses species were estimated and given in **Table 9**. The average litter accumulation was found 3.77 t/ha in the present study. Jamaludheen and Kumar (1999) estimated the annual litter production range from 3.43 t/ha (*Pterocarpus*) to 12.69 t/ha (*Acacia*) in 8-9 year old woodlots of 9 fast growing tree species in Kerala.

The average litter accumulation for *D. sissoo* leaves and branches was found 3.04 t/ha in the present study. Litterfall data for forest floor of Bhabar Shisham forests (5 years age) in central Himalaya was estimated 2.9 t/ha (Lodhiyal and Lodhiyal, 2002). Total Carbon content in the accumulated litter layer was calculated by assuming 40% carbon content is in the litter and CO_2 sequestered by litter component accounts 5.33 t/ha for a 3 year period (assuming the age of reclamation is 3 years) in the present study. Therefore CO_2 sequestered through the litter component in t/ha/yr is calculated as 1.84t/ha/yr.

4.1.5 Analysis of mine soils properties

Soil samples were collected underneath various tree species and analyzed two times as described in section 2.2.1. Physiochemical characteristics of soil samples (collected on 28. 01. 2015) were analyzed as per the standard methods (**Table 10**). The value of soil paste pH were range between 6.11 - 6.75, average of 6.56, whereas pH (1:2.5; w/v) within 6.35 - 6.71 range and higher average value than the paste pH (6.63). Electrical conductivity was found within the range 0.12 - 0.30 dS/m average 0.22 dS/m, which is suitable for plant growth. Soil organic carbon was determined by Walkley and Black method and found high (3.68 - 6.13%) due presence of coal carbon in the dump site. Exchangeable K was found highest underneath Bamboo and *A. lebbeck* with average value of 194.67 ppm whereas, Na values were found to be much lower within the range of 14 – 32 ppm and the highest value of ex-K was found underneath *A. lebbeck* tree (32 ppm).

Table 9: Litter accumulation and CO_2 sequestration at Tetulmari ecorestoration site. (Size of quadrate: 0.5m x 0.5 m and area of sampling= $0.25m^2$; date of study: 21.7.2015)

Sl no.	Location of litter collection	Fresh weigh of litter (g)	Moisture free dry weight of litter (g)	Moisture content (%)	Dry weight of litter (kg)	Litter accumulated (kg/m^2)	Litter accumulated (t/ha)
		a	b	c = [(a-b)/a]*100	d = b/1000	e = d/0.25	f=e*10
1.	*Grass* + *D. sissoo* leaves & branches	164	83	49.39	0.083	0.332	3.32
2.	*D. sissoo* leaves & branches	124	76	38.71	0.076	0.304	3.04
3.	*P.pedicellatum* grass	134	100	25.37	0.1	0.400	4.00
4.	Grass + *D. sissoo* leaves & branches	156	82	47.44	0.082	0.328	3.28
5.	Grass + D. sissoo leaves & branches	251	141	43.82	0.141	0.564	5.64
6.	Grass + *B. arundanacea* leaves & branches	202	124	38.61	0.124	0.496	4.96
7.	Grass + *D. sissoo* leaves & branches	115	84	26.96	0.084	0.336	3.36
8.	Grass + *D. sissoo* leaves & branches	165	64	61.21	0.064	0.256	2.56
						Average ± SD (Min- Max)	**3.77±0.41 (2.56-4.96)**

[1]. Total Area of Tetulmari site = 8 ha

[2]. Average litter accumulation in the ecorestoration site = 3.77 t/ha

[3]. Total carbon content in litter accumulated (assuming 40% carbon) = (3.77 x 0.4)=1.508 tons

[4]. CO_2 sequestered by litter accumulation/ ha area (multiply factor of 3.67, to convert C to CO_2) = (1.508 x 3.67) = **5.53 t/ha**

[5]. CO_2 sequestered by litter accumulation/ha/year (assuming the age of reclamation is 3 yrs) = (5.53/3) = **1.84 tons/ha/yr**

Table 10: Physiochemical characteristics of soil samples collected underneath the tree species at Tetulmari ecorestoration site (Date of soil sampling: 28.02. 2015)

Soil parameters	*D. sissoo*	*B. arundanacea*	*F. infectoria*	*D. viscose*	*A. indica*	*A. lebbeck*	Avg value ±SD (Min-Max) (CV%)
pH(1:1)	6.71	6.4	6.11	6.75	6.66	6.7	6.56 ± 0.25 (6.11 - 6.75) (3.83)
pH(1:2.5)	6.70	6.52	6.35	6.71	6.68	6.79	6.63 ± 0.16 (6.35 - 6.71) (2.43)
EC (dS/m)	0.12	0.17	0.24	0.25	0.23	0.300	0.22 ± 0.07 (0.12 - 0.30) (29.65)
Organic C (%)*	**5.11**	**4.21**	**4.62**	**6.13**	**5.34**	**3.68**	**4.85 ± 0.87 (3.68 - 6.13) (17.91)**
Exchangeable K (ppm)	190	147	144	123	108	156	194.67 ± 28.30 (108 - 190) (14.54)
Exchangeable Na (ppm)	17	15	14	17	20	32	19.17 ± 6.62 (14 - 32) (34.51)
Available P (ppm)	0.57	2.18	2.29	1.93	1.96	2.18	1.85 ± 0.64 (0.57 - 2.29) (34.69)
Available N (ppm)	69	78	82	95	75	136	89.17 ± 24.54 (69 - 136) (27.52)

* By Walkley – Black (rapid dichromate digestion) method

Soil samples were collected with a soil corer underneath Deenanath grass vegetation at the top of the dump at a depth 0-15cm and 15-30 cm [labeled as S-1 (0-15 cm) and S-1a (15-30 cm) respectively. Other samples collected underneath different tree species (*A. indica* and *D. sissoo*) labeled as S2 (0-15 cm) and S3 (0-15 cm).respectively. Some samples were also collected at the toe of the dump, labeled as S7 (0-15 cm) and S8 (0-15 cm) (**Table 11)**.

Following observations may be drawn based on the physiochemical characteristics of restored sites:

a) **Soil fraction % (<2mm size)** was analyzed to determine the percentage of the soil in the vicinity of the plant roots and can supports the plants growth. Soil fraction was estimated between the **34.51% - 60.56%** indicating high habitat heterogeneity. Estimated higher value of the soil fraction [sample S2 (0-15 cm] shows that rhizosphere of *A. indica* tree is supported by the higher percentage of the soil which accounts for its good growth. While soil fraction was found low underneath grass vegetation [S4 (0-15 cm)]. The average value of soil fraction for the entire sampling site (8 nos) was 46 %. The uneven distribution of soil fraction was mainly characterized by the plants roots and their rhizospheric functions. Similarly, average course fraction estimated in the site was found 57%.

b) **Soil paste pH (1:1 w/v) and pH (1:2.5, w/v)** of the soil samples were measured and the average value found nearly alkaline. Paste pH (1:1 w/v) was found within the range of 5.74 - 7.98 (average value-7.13). Similarly, pH (1:2.5, w/v) was measured for all the eight samples and average value was found slightly high as 7.24. The pH of the mine soils mainly depend on the substrate and nature of the geological material of the earth crust and the tree species.

c) **Electrical conductivity** is the measure of the ions present in the samples and mainly depends on the nature of the substrate and salts release by the roots of plants and trees. At Tetulmari ecorestoration site, it is found within the range of 0.16-0.39 dS/m, which is suitable for the plant growth.

Table 11: Physiochemical characteristics of soil samples collected from Tetulmari Ecorestoration site (Date of Sampling: 12.3.2015)

Soil properties	S-1	S1a – (15-30 cm)	S-2	S-3	S-4	S-5	S-6	S-7	S-8	Avg value ± SD (Min-Max) (CV%)
Soil fraction (<2mm size) %	42.58	38.84	60.56	40.74	34.51	46.95	42.82	49.55	53.17	45.52 ± 7.97 (34.51 - 60.56) (17.50)
Non-soil fraction (>2mm size) %	57.42	61.16	59.9	59.26	65.49	53.05	57.18	50.45	46.83	56.75 ± 5.75 (46.83 - 65.49) (10.13)
pH (1:1)	6.86	6.85	6.61	7.88	7.38	7.98	7.3	5.74	7.55	7.13 ± 0.70 (5.74 - 7.98) (9.80)
pH (1:2.5)	6.91	6.98	6.68	8.01	7.4	8.14	7.36	5.91	7.76	7.24 ± 0.70 (5.91 - 8.01) (9.73)
EC (1:2.5) (dS/m)	0.21	0.16	0.19	0.261	0.247	0.206	0.203	0.39	0.253	0.23 ± 0.07 (0.16 - .39) (28.36)
Moisture content (%)	3.83	4.37	2.14	4.26	2.87	2.35	3.72	4.17	5.59	3.70 ± 1.09 (1.72 - 7.17) (29.48)
SOC (%) *	5.62	4.38	4.60	3.67	5.10	6.12	4.62	5.34	4.21	4.85 ± 0.76 (3.67 - 6.12) (15.70)
Av.N (mg/Kg)	69	78	82	95	75	136	110	98	128	96.78 ± 23.74 (69 - 128) (24.53)
Av-P(mg/Kg)	2.18	1.87	2.86	1.93	1.96	2.18	1.82	2.26	2.18	2.14 ± 0.31 (1.87 - 2.86) (14.66)

* By Wakley – Black (rapid dichromate digestion) method

d) **Moisture content** was found moderate in the mine soil samples and range between 1.72 – 5.59 % due to the restriction of the water by the plain surface at the top of the dump site and may be due to the higher litter fall.

e) **Soil organic carbon (SOC)** were estimated by the rapid dichromate method for all the samples and found much higher within the range of 3.67 - 6.12 %, and average value of OC% is 4.85 %, due to presence of higher amount of coal carbon in the soil samples. The coal carbon in the samples was estimated by the method described by Ussiri and Lal (2008).

f) **Plant available nitrogen** was found highest in sample S5 (0-15 cm (136 mg/kg), may be due to presence of some leguminous plants or trees which supports nitrogen fixation. N of all the eight samples were estimated within the range 69 – 136 mg/kg (average 96.78 mg/kg), which is suitable for the plant growth and also showed the nitrogen fixing potential of the various plant species found on the restored dump.

g) **Plant available phosphorus** is the limiting factor for the plant growth. The estimated values of the available P were range between 1.87 - 2.86 mg/kg, suitable for plant growth.

h) **Total soil carbon (TSC)** analyzed for all the samples collected from Tetulmari restoration site was found in the range of 2.01 – 2.90 % and the average value was 2.36 %. (**Table 12**). After 1 M HCL treatment of the soil samples, IC % was analysed by CHNS analyzer; about 9% of TSC (average 0.21 % within a range of 0.17 – 0.26 %). Coal carbon % was determined by C fractionation method described by Ussiri and Lal (2008). Average value of coal carbon was calculated as 1.07 % (about 45 % of TSC).The IC % and coal carbon % was substracted from the TSC to determine the organic portion, biogenic carbon which is used for CS calculation from minesoil. It was found in the range of 0.94 - 1.26 % (average value of 1.08 %) Distribution of Total carbon (%), Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) of different mine soil samples at Tetulmari eorestoration site is shown in **Fig 5.**

Table 12: Proportion of Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) present in mine soil samples of Tetulmari ecorestoration site

No. of samples	Total soil carbon (%)	Inorganic carbon (%)	Coal carbon (CC)%	Biogenic Carbon (BC) (%)
	a	b	c	d = a-(b+c)
1	2.13	0.17	0.95	1.01#
2	2.01	0.19	0.87	0.94
3	2.56	0.22	1.14	1.20
4	2.21	0.20	1.01	1.00
5	2.90	0.26	1.39	1.26
Avg ±SD (Min-Max)	**2.36±0.36 (2.01-2.90)**	**0.21±0.03 (0.19-0.26)**	**1.07±0.20 (0.87-1.39)**	**1.08±0.14 (0.94-1.26)**

2.13- (0.17 + 0.95) = 1.01

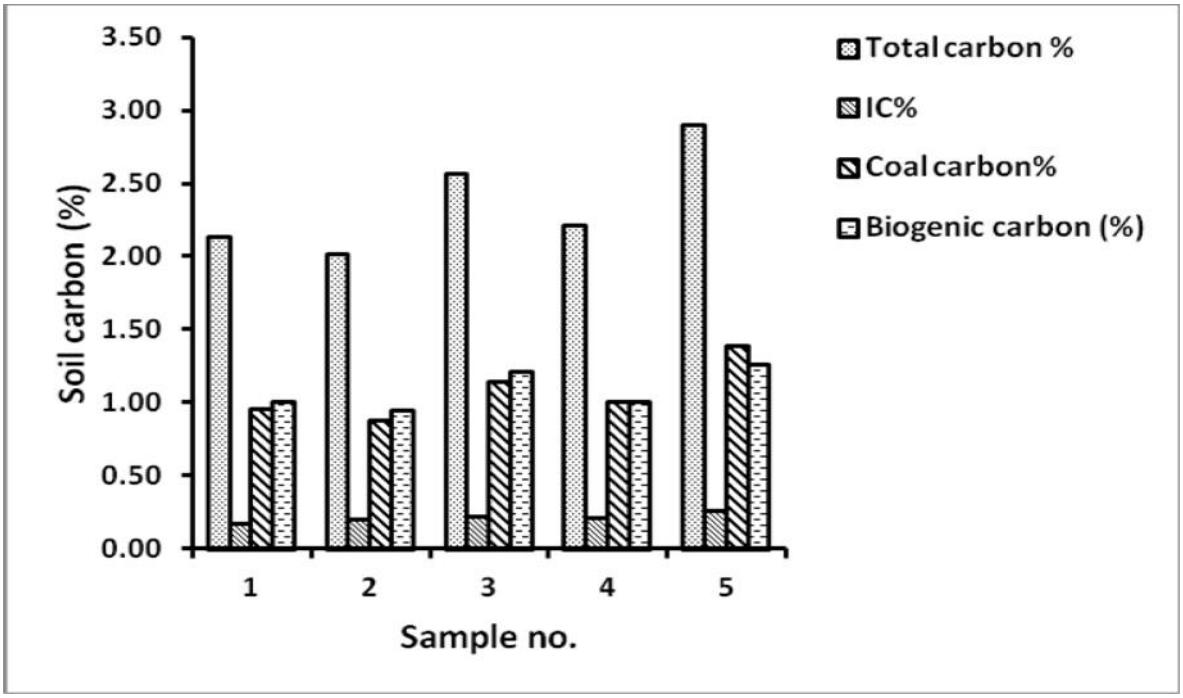

Figure 5: Distribution of Total carbon (%), Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) of different mine soil samples at Tetulmari ecorestoration site.

4.1.6 Estimation of the CO_2 sequestration of minesoil

The C-sequestration potential of any ecosystem is presumed to increase as community structure and associated mine soils development. The ecological restoration practices can considerably increases the C-sequestration potential of mine degraded land. The photosynthesis process assimilates carbon dioxide *vis-a-vis* increase biomass which also develops SOM pools. A key objective in C sequestration research is to enhance the capacity and ability of plants and soils to sequester C.

Establishment of biomass due to revegetation in mine soils leads to accumulation of SOC and plays crucial role in restoration by regaining the lost C by absorbing it from atmosphere. An increase in biomass up to 12 years of natural revegetation was reported by Singh and Singh (1999) in dry tropical conditions. Mature woody trees have more C sequestration potential as compared to the young trees. For, an example, C sequestration was found to be 95% higher in woody trees as compared to herbaceous vegetation (Dean et al., 2012). Thus the rate of carbon accumulation depends on fast growth of trees, increment in diameter and development of roots. However, different types of mine spoil affect survival and growth rates of different tree species, which depend on nature of species and management practices.

Tripathi et al. (2014) reported annual C sequestration potential of 3.64 t C $ha^{-1}yr^{-1}$ of revegetated mine spoils. The distributed C in plant biomass was 44.5 t ha^{-1}, in mine soil 22.9 t ha^{-1} and 1.8 t ha^{-1} in microbial biomass. They also compared the C sequestration rates of RMS and forest ecosystem in US and Indian conditions. Average CO_2 sequestration rate in US minesoil reclaimed to forest was 6.32 Mg $ha^{-1}yr^{-1}$, while the potential CO_2 sequestration rate in forest ecosystem (biomass, soil and litter) was 9.4 Mg $ha^{-1}yr^{-1}$. Soil C sequestration rate in Indian RMS was 20 Mg $ha^{-1}yr^{-1}$, while total C sequestration rate through soil, biomass and litter mass was 9.36 Mg $ha^{-1}yr^{-1}$. Total C sequestered in RMS is equivalent to 253.96 tons per ha (t ha^{-1}) capture of atmospheric CO_2 which indicates that mine spoil can act as a significant sink for atmospheric CO_2 through revegetation Thus total annual C budget was calculated as 8.40 t C $ha^{-1}yr^{-1}$ accumulation out of which 2.14 t ha^{-1} was allocated in above ground biomass, 0.31 t ha^{-1} in belowground biomass, 2.88 t ha^{-1} in litter mass and 1.35 t ha^{-1} in mine soil.

Total soil C content in RMS consists of three types of pools namely; (i) soil inorganic C (SIC), (ii) geogenic C (coal-C or fossil C) and (iii) biogenic C (plant derived recent SOC). Sources of SIC are parent rock of overburden materials which consists of carbonates, but can also be found as calcite and dolomite in significant concentrations."Geogenic C" in minesoils originates from the incorporation of coal particles or coal dust during overburden removal, coal mining and reclamation operations while "biogenic C" originates from recent biological inputs. Microbial decomposition of biogenic C sources (litter) along with different pedogenic process leads to their mixing with geogenic C. Also, the humus and coal particles due to their same dark color cannot be easily identifiable. The stable fractions of "biogenic C" such as the humus and mineralizable fractions are responsible for maintaining long term CO_2 sequestration as it controls the SOC pool. Standard procedures for quantifying SOC concentrations in RMS such as the chemical wet oxidation or dry combustion methods cannot distinguish geogenic C from biogenic C in RMS. This leads to overestimation of C pools and sequestration rates since the rates of change in SOC are quite small as compared to the large amounts of SOC often present which must be measured.

Based on data in the literature, many researches opined that sites reclaimed as grasslands and deciduous forests accumulated SOC faster than forests. In addition, Literature suggested that in many case, post-mining sites reaches their pre-mining SOC stock within 20 years or less after reclamation. Estimation of carbon sequestration in mine soil samples at Tetulmari ecorestoration site was based on soil organic carbon (SOC) (%), bulk density (g/cc or t/m3) and depth (m) of soil using the following equation (Lal et al., 1998):

$$\textbf{Mg C ha}^{-1} = [\%C * \textbf{Corrected } B_d * \textbf{d (m)} * 10^4 \textbf{ m}^2 \textbf{ ha}^{-1}] /100$$

Where, Mg C ha^{-1} is Mega grams C per hectare (tons / ha),

B_d (Mg m^{-3}) is the corrected soil bulk density, (g/cc) and d is the soil depth (m).

%C is the biogenic carbon calculated from total soil carbon by substracting the coal carbon % and inorganic carbon % from it.

C-sequestration from minesoil of the Tetulmari site was estimated as 17.89 t/ha on the basis of biogenic carbon, bulk density and depth whereas the CO_2 sequestered from the minesoil of the site was calculated as 65.65 t/ha (**Table 13(a)**).

Table 13 (a): Estimation of CO_2 sequestration of soil samples at Tetulmari ecorestoration site, based on Biogenic Carbon (%), corrected Bulk density (g/cc) and Depth (m) of soil.

No. of samples	Biogenic Carbon (BC) (%)	Corrected Bulk Density (g/cc)	Depth (m)	C sequestered in mine soil (t/ha)	CO_2 sequestered in mine soil (t/ha)**
1	1.01	1.16	0.15	17.53*	64.32
2	0.94	1.12	0.15	15.86	58.20
3	1.20	1.02	0.15	18.42	67.60
4	1.00	1.15	0.15	17.25	63.32
5	1.26	1.08	0.15	20.38	74.79
Avg ± SD (Min - Max)	**1.58±0.3 (1.34-1.98)**	**1.11±0.1 (1.02-1.16)**	**0.15**	**17.89± 1.67 (15.86- 20.38)**	**65.65± 6.13 (58.20- 74.79)**

***** C sequestered (t/ha) = [%BC * Corrected B_d * d (m) *10^4 m^2 ha^{-1}] /100
= [1.01 x 1.16 x .15 x 10000]/100 = 17.33 t/ha

****** CO_2 sequestered (t/ha) = 17.53 t/ha x 3.67 = 64.32 t CO2 sequestered/ha

4.1.7 Estimation of total CO_2 sequestration of Tetulmari ecorestoration site

Total CO_2 sequestration of Tetulmari ecorestoration site is estimated by calculating the C stock of (i) AGB of tree and bamboo plantation, (ii) litter & (iii) minesoil components. Next the C stock is converted to CO_2 equivalent (t of CO_2 sequestered/ha) & given in **table 13 (b).**

Table 13 (b): Estimation of total CO_2 sequestration of Tetulmari ecorestoration site

Sl. no.	Different components of CO_2 sequestration	Total C stock (t/ha)	CO_2 sequestered (t/ha)
1	Aboveground & Belowground biomass	38.73	142.15
2	Litterfall	1.508	5.533
3	Soil	17.89	65.65
Total		58.128	213.33

4.2 Damoda old Ghutway ecorestoration Site-1

4.2.1 Determination of density and relative density of plant species

Three quadrates of size 10m x 10m were laid down in the site and species found is given in Table 1(a). In 3 quadrate (equal to 300 m^2), 75 nos of trees were recorded, and *Albizia lebbeck* (57%) and *Dalbergia sissoo* (33%) together constitutes 90% of total plants population followed by *Phyllanthus emblica* (4%), *Mitragyna parviflora* (2%), *Syzizium cumini* (1%) and *Zizypus mauritiana* (1%). Relative distribution of tree species in Damoda ecorestoration Site 1 is shown in **Fig 6 (a & b).** The tree density was calculated as 2500/ha and total nos of trees in 4 ha of dump estimated 10,000 nos. The details of density of tree/ha, total estimated tree count, ecological frequency, frequency class, abundance and density of individual tree/ha is given in **Table 14(a).**

During the quadrate survey, a total of 48 saplings were noted in 300 m^2 of the area **(Table 14b).** The nos of saplings found in each quadrat varied from 14 to 17 nos. Seven tree species found in the quadrat was considered for the C sequestration study whereas thirteen species of saplings were found less than 1.5 height, were not considered for biomass estimation and CS study. Among the saplings, highest density was contributed by *Phyllanthus emblica (19%), Albizia lebbeck, D. sissoo* and *Terminalia arjuna (15%* each*)*, followed by *Lannea coromandelica* (10%), and the rest by others (2-6%). Total number of saplings was estimated as 1600 nos. /ha and in 4ha, total saplings was calculated as 6400 nos. Total Sixty one nos of bamboo clumps were observed in the three quadrats. Therefore the density of bamboo clumps was calculated as 2033 clumps/ha; total clumps in 4 ha area of the dump was 8132 nos. A total of 33 nos of species were observed in the Damoda ecorestoration site-1 out of which only 13 nos species were present in the quadrate including different grasses, bamboo and saplings of trees. Types of vegetation in the Damoda ecorestoration site 1 is given in table **Table 15.**

4.2.2 Measurement of Diameter at Breast Height (DBH) of tree species

Diameter at Breast Height (DBH) of tree species were measured for the estimation of above ground biomass (ABG) and root biomass of tree species by using allometric equation. DBH of all the 75 trees were measured by using Vernier caliper and measuring tape. Details of measurement of DBH are given in **Table 16.**

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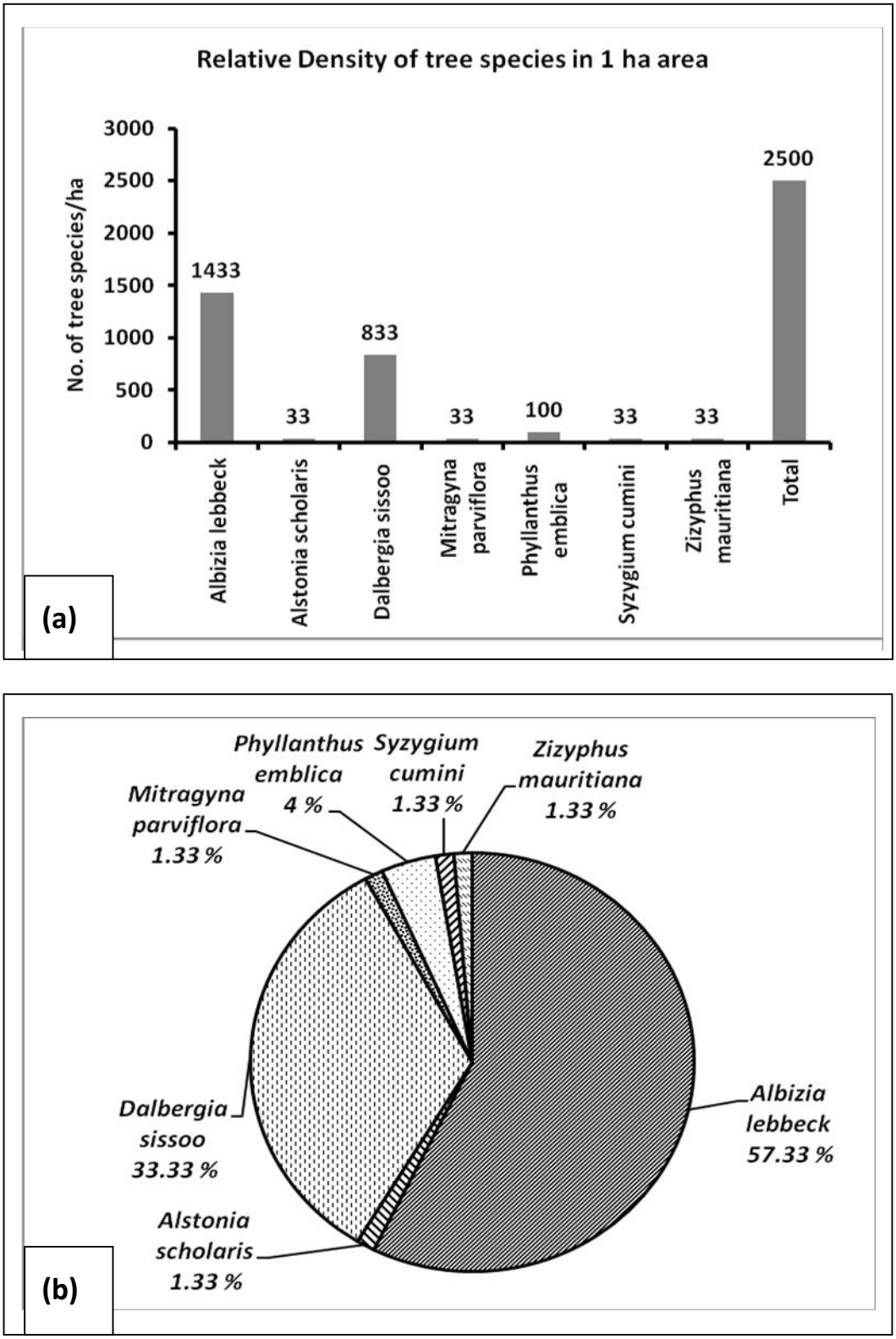

Figure 6(a & b): Relative distribution of tree species in Damoda ecorestoration Site 1

Table 14(a): List of species recorded in quadrate of **Damoda ecorestoration Site 1**, showing frequency (%), density (trees/ha), relative density and abundance. (Size of quadrat in this study: 10m x 10m=100m^2) (Date of sampling: 25.7.2015)

Sl no	Name of sp	Quadrats Nos			Total no of individual	Total no of quadrats of occurance	Total no of quadrats studied	Frequency (%)	Frequency class	Density (individual/unit area)	Density(per hectare)	Abundance	% of the total no of species
		1	2	3									
1	*Albizia sp*	15	17	11	43	3	3	100.00	E	14.33	1433	14.33	57
2	*Alstonia scholaris*	-	1	-	1	1	3	33.33	B	0.33	33	1	1
3	*Dalbergia sissoo*	8	9	8	25	3	3	100.00	E	8.33	833	8.33	33
4	*Mitragyna parviflora*	-	1	-	1	1	3	33.33	B	0.33	33	1	1
5	*Phyllanthus emblica*	-	2	1	3	2	3	66.67	D	1.00	100	1.5	4
6	*Syzygium cumini*	-	-	1	1	1	3	33.33	B	0.33	33	1	1
7	*Zizyphus mauritiana*	-	-	1	1	1	3	33.33	B	0.33	33	1	1
	Total=	23	30	22	**75**						**2500**		

No of trees in 300 m^2 = **75 nos.**
No of trees (>1.5m height) in 1 ha = (75/300)*10000 = **2500 trees/ha.**
Density of trees in total 4 ha Damoda Ecorestoration site 1 = 2500 nos/ha*4ha = **10,000 nos**

Table 14 (b): List of saplings of height <1.5 m and Bamboo clumps observed in the quadrate of Damoda ecorestoration site 1. (Size of quadrat: 10m x 10m=100m^2)

Sl no.	Tree species	Quadrates laid down			Total no of saplings	Relative Density (%)
		1	2	3		
1	*Adina cordifolia*	-	3		3	6
2	*Albizia lebbeck*	2	4	1	7	15
3	*Bauhunia variegata*	1	1		2	4
4	***Bambusa arundanacea (clumps)***	**25**	**17**	**19**	**-**	**-**
5	*Butea monosperma*	1	1	-	2	4
6	*Dalbergia sissoo*	3	2	2	7	15
7	*Lannea coromandelica*	1	-	4	5	10
8	*Madhuca indica*	1	-	-	1	2
9	*Mangifera indica*	-	-	1	1	2
10	*Phyllanthus emblica*	3	2	4	9	19
11	*Tectona grandis*	-	-2	-	2	4
12	*Terminalia arjuna*	3	2	2	7	15
13	*Terminalia tomentosa*	2	-	-	2	4
	Total=	42[a]	34[b]	33[c]	**48[d]**	

[a] 17+ (Bamboo clumps-25); **[b]** 17+ (Bamboo clumps-17); **[c]** 14+ (Bamboo clumps-19)

[d] excluding 61 nos bamboo clumps

No of saplings in 300 m^2 = 48 nos of <1.5 m saplings (excluding 61 nos bamboo clumps)

No of saplings in 1 ha = (48/300)*10000 =1600 nos of saplings/ha & (61/300)*10000 = 2033 nos of bamboo clumps /ha

So, Density of plantation:

a) Saplings in total 4 ha area of the site = 1600 saplings/ ha x 4 ha = **6400 nos of saplings**.

b) Bamboo in total 4 ha area of the site = 2033 nos. of bamboo/ha x 4 ha = **8132 no of clumps**

Table 15: Type of Vegetation in Damoda ecorestoration site 1

Sl no.	Type of plantation	Common name	Botanical name	Family
1	Trees	Sisham (Sissoo)	*Dalbergia sissoo*	Fabaceae
2		Neem (Margosa tree)	*Azadirachta indica*	Meliaceae
3		Bakain (Ghora neem)	*Melia azedarach*	Meliaceae
4		Pakur (Pakar)	*Ficus infectoria*	Moraceae
5		Karanj (Indian Beech)	*Pongamia pinnata*	Fabaceae
6		Kachnar (Kanchan)	*Bauhinia variegata*	Fabaceae
7		Kala Siris	*Albizia lebbeck*	Fabaceae
8		White Siris	*Albizia procera*	Fabaceae
9		Palash (Flame of the forest)	*Butea monosperma*	Fabaceae
10		Chatim (Indian devil tree)	*Alstonia scholaris*	Apocynaceae
11		Amla (Indian gooseberry)	*Phyllanthus emblica*	Phyllanthaceae
12		Arjun	*Terminalia arjuna*	Combretaceae
13		Jhingam (Doka/ Indian ash tree)	*Lannea coromandelica*	Anacardiaceae
14		Mahua	*Madhuca indica*	Sapotaceae
15		Asan (Black Murdah)	*Terminalia tomentosa*	Combretaceae
16		Teak	*Tectona grandis*	Lamiaceae
17		Haldu	*Adina cordifolia*	Rubiaceae
18		Gulikadam (Kaim)	*Mitragyna parviflora*	Rubiaceae
19		Amaltas	*Cassia fistula*	Fabaceae
20		Indian almond	*Terminalia catappa*	Combretaceae
21	Grasses	Dennanath	*Pennisetum pedicellatum*	Poaceae
22		Kash	*Saccharam munja*	Poaceae
23		Kans	*Saccharam benghalense*	Poaceae
24		Kans	*Saccharam spontaneum*	Poaceae
25		Kash	*Saccharam munja*	Poaceae
26		Sui ghas	*Cenchrus ciliaris*	Poaceae
27		Dhaman grass	*Cenchrus setigerus*	Poaceae
28		Doob grass	*Cynodon dactylon*	Poaceae
29		Bamboo (thorny bamboo)	*Bambusa arundanacea*	Poaceae
30	Shrubs	Ber (Indian plum)	*Ziziphus mauritiana*	Rhamnaceae
31	Fruit trees	Jamun	*Syzygium cumini*	Myrtaceae
32		Mango	*Mangifera indica*	Anacardiaceae
33		Guava	*Psidium guajava*	Myrtaceae

Table 16: Classification of tree species based on DBH at Damoda ecorestoration site 1

Name of Tree species	Occurrence of species in Quadrat no.	Circumference (cm)	DBH (cm)	No of trees in each quadrat (n)
Albizzia spp (n*=43)	1	17	5.41	15
		23	7.32	
		39	12.42	
		20	6.37	
		22	7.01	
		18	5.73	
		15	4.78	
		14.2	4.52	
		16	5.10	
		12	3.82	
		10	3.18	
		20	6.37	
		18	5.73	
		14	4.46	
		18	5.73	
	2	30	9.55	17
		28	8.92	
		29.2	9.30	
		32	10.19	
		11	3.50	
		15	4.78	
		14	4.46	
		16.4	5.22	
		13.3	4.24	
		18	5.73	
		22	7.01	
		20.6	6.56	
		11	3.50	
		10.2	3.25	
		10	3.18	
		18.4	5.86	
		14	4.46	
	3	18.6	5.92	11
		22	7.01	
		14	4.46	
		10.8	3.44	

		12	3.82	
		16	5.10	
		14.5	4.62	
		15.4	4.90	
		19	6.05	
		20.2	6.43	
		21	6.69	
Alstonia scholaris (n=1)	2	10	3.18	1
Dalbergia sissoo (n=25)	1	15	4.78	8
		14	4.46	
		18	5.73	
		16	5.10	
		24	7.64	
		12	3.82	
		18	5.73	
		20	6.37	
	2	18	5.73	9
		12	3.82	
		15	4.78	
		16	5.10	
		14.5	4.62	
		13	4.14	
		18	5.73	
		19.5	6.21	
		20	6.37	
	3	14	4.46	8
		16.4	5.22	
		18	5.73	
		12.2	3.89	
		19.8	6.31	
		20.8	6.62	
		24	7.64	
		16	5.10	
Mitragyna parviflora (n=1)	2	12	3.82	1
Phyllanthus emblica (n =3)	2	10	3.18	2
		12	3.82	
	3	10	3.18	1
Syzygium cumini (n =1)	3	15	4.78	1
Zizyphus mauritiana (n =1)	3	12	3.82	1
			Total =	**75**

4.2.3 Estimation of above ground biomass (AGB) and Root biomass and CO_2 sequestration

Estimation of above ground biomass (AGB) and Root biomass at Damoda ecorestoration site-1 based on DBH classes of individual tree species is described in **Table 17**. Density of tree species used for CS study at the Damoda site-1 was 2500/ha. The seven species were classified within the DBH classes, (e.g. *A. lebbeck* trees were classified within 5 DBH classes ranging from 3-5cm, 5-7cm, 7-9cm, 9-11cm and 11-13cm). Among these DBH classes, a count of number of trees per hectate was estimated (e.g. among all the 5 DBH classes, a total of 1433 nos of *A. lebbeck* / ha was calculated; no of trees present in 300 m^2 was 43 nos.). Then average DBH of trees was calculated and put into the allometric equation (Brown 1997), which is also used in the FAO (1997) to estimate the AGB. Details of AGB calculation by Brown (1997) equation as published in FAO web site (given *Annexure -2.)*The AGB values were used for calculating BGB or RB by MacDicken (1997) equation. Out of 7 species, *A. lebbeck,* contributed maximum biomass (13.04 t/ha AGB and 2.61 t/ha RB), At the higher DBH class, both AGB and UG biomass increased in exponential manner (*Annexure -1*).

In **Table 18**, total estimation of above ground biomass (AGB) and BGB was done by adding up the AGB and BGB of all individual tree species (converting to t/ha). We have seen that the density of bamboo clumps is very high in this ecorestoration site. Hence, in this study carbon sequestration by bamboo plantation was calculated by considering the work of Singh and Singh (1999). Details of calculation of biomass of bamboo plantation and CO_2 sequestration from total biomass (tree + bamboo) is given in **section 3.5.1**.

The total tree biomass (Brown equation, 1997) was estimated 23.61 t/ha and the corrected biomass of bamboo clumps was calculated as 5.28 t/ha. Thus the total biomass (tree

and bamboo) was calculated as 28.89 t/ha. The carbon stock of the tree and bamboo biomass of 28.89 t/ha is equal to 14.45 t/ha (a factor of 0.5 is multiplied to convert the amount of carbon fixed in the biomass). The conversion factor of 0.5 is taken from FAO (1997). Next, the amount of CO_2 sequestered per hectare was calculated as 53.03 t of CO_2/ha. The CO_2 sequestered by the tree and bamboo biomass in4 ha area of the ecorestoration site at Damoda old Ghutway site-1 is calculated as 212.12 tons. Whereas, the rate of CO_2 sequestered at the site was calculated as 17.68 tons CO_2 /ha/yr.

Terakunpisut et al. (2007) assessed the C sequestration on the aboveground biomass in different forest ecosystems of Thong Pha Phum National Forest, Thailand based on DBH ≥ 4.5 cm using allometric equation (conversion factor 0.5 used for C-stock). Tropical rain forest had higher C stock than dry evergreen forest and mixed deciduous forest in order of 137.7 ± 48, 70.3± 7.4 and 48± 16.7 t C ha^{-1}, respectively.

4.2.4 Estimation of CO_2 sequestration in litter

Litter accumulation is also an important parameter for consideration in the C sequestration study. Litter accumulation underneath different trees, grasses and bamboo were estimated in this study. The average litter accumulation was found 2.45 t/ha in the present study at Damoda ecorestoration site 1 (**Table 19**).

Total Carbon content in the litter was calculated by assuming 40% carbon content is in the litter and CO2 sequestered by litter component amounts to 3.59 t/ha for a 3 year period (assuming the age of reclamation is 3 years). Therefore CO_2 sequestered through the litter component in t/ha/yr is calculated as 1.20t/ha/yr.

Table 17: Estimation of above ground biomass (AGB) and root biomass (RB) based on DBH (Diameter at Breast height) class for individual tree species (no of trees/ha = 2500) at Damoda ecorestoration site 1.

Tree species name	DBH range (cm)	Avg DBH (cm)	No of trees in 300m^2	No of trees/ha[3]	AGB of trees (kg)[1]	AGB of all trees (t/ha)	Root biomass (RB) (t/ha)[2]
Alzebia. lebbeck	3- 5	4.08	18	600**	3.54*****	2.12#	0.42##
	5 - 7	5.88	16	533	8.27	4.41	0.88
	7 - 9	7.91	6	200	16.47	3.29	0.66
	9 - 11	9.43	2	67	24.76	1.65	0.33
	11- 13	12.42	1	33	46.94	1.56	0.31
		Total	**43**	**1433**	**99.97**	**13.04**	**2.61**
Alstonia scholaris	3- 5	3.18	1	33	2.00	0.07	0.01
		Total	**1**	**33**	**2.00**	**0.07**	**0.013**
Dalbergia sissoo	3- 5	4.31	9	300	4.02	1.21	0.24
	5 - 7	5.80	14	467	8.02	3.74	0.75
	7 - 9	7.64	2	67	15.22	1.01	0.20
		Total	**25**	**833**	**27.26**	**5.96**	**1.19**
Mitragyna parviflora	3- 5	3.82	1	33	3.05	0.10	0.02
		Total	**1**	**33**	**3.05**	**0.10**	**0.02**
Phyllanthus emblica	3- 5	3.40	3	100	2.32	0.23	0.05
		Total	**3**	**100**	**2.32**	**0.23**	**0.05**
Syzygium cumini	3- 5	4.78	1	33	5.11	0.17	0.03
		Total	**1**	**33**	**5.11**	**0.17**	**0.03**
Zizyphus mauritiana	3- 5	3.82	1	33	3.05	0.10	0.02
		Total	**1**	**33**	**3.048**	**0.10**	**0.02**

[1] Calculated by Brown (1997) equation:

Y (biomass in kg) = exp (-1.996 + 2.32 * ln DBH (cm));

= exp (-1.996 +2.32 * ln (4.08)) = 3.54 kg (*)

[3]No of trees/ ha = (No. of trees in 300 m2 / 300) x 10000

****** (18/300) x 10000 = 600 no of trees / ha

[#] 3.54 kg x 600 (no of trees/ha) x 10^{-3} (conversion factor of biomass; kg to tons) = 2.12 (t/ha)

[2] Calculated by MacDicken (1997) formula: Root biomass = above ground biomass (t/ha) x 0.2

[##] 2.12 (t/ha) x 0.2 = 0.42 (t/ha)

Table 18: Estimation of total above ground biomass (AGB) and root biomass (RB) of tree and bamboo [by using Brown (1997), MacDicken (1997) equation] and CO_2 sequestration. at Damoda ecorestoration site 1

Tree species name	No of trees/ ha	Total AGB of tree species (t/ha)[1]	Total RB of tree species (t/ha)[2]	**Total biomass (AGB+RB) (t/ha)**
	a	b	c	d (b +c)
Albizia spp	1433	13.04	2.61	15.65
Alstonia scholaris	33	0.07	0.01	0.08
Dalbergia sissoo	833	5.96	1.19	7.16
Mitragyna parviflora	33	0.10	0.02	0.12
Phyllanthus emblica	100	0.23	0.05	0.28
Syzygium cumini	33	0.17	0.03	0.20
Zizyphus mauritiana	33	0.10	0.02	0.12
Total	2500	19.68	3.94	**23.61**

[*] All the values in column a, b and c obtained from **Table 7**

[1] Values calculated by Brown (1997) equation;

[2] Values calculated by MacDicken (1997) formula

Total tree biomass (above ground and root biomass) = **23.61 tons/ha**

Bamboo density (nos of clumps/ha)	Average biomass (t/ha)*	Corrected Biomass (tons/ha)**
2033	13.21	5.28

*Average biomass (t/ha) = density of bamboo x 0.006525 = 2033 bamboo shoots / ha x 0.0065 = 13.21 t/ha.

The factor 0.0065 is derived from Singh & Singh (1999) (26.1 t/ha / 4000 nos/ha = 0.0065).

Corrected Biomass (t/ha) = 40% of biomass is considered due to young age of bamboo plantation = 13.21 t/ha x 0.4 **= 5.28 tons/ha

Total biomass of tree and bamboo plantation = 23.61 + 5.28 = **28.89 t/ha**

Carbon stock of trees and bamboo = 28.89 t/ha x 0.5 (factor to convert amount of C fixed in the biomass) = **14.45 t/ha**

CO_2 sequestered = 14.45 t/ha x 3.67 (factor to convert C to CO_2) = **53.03 t/ha**.

CO_2 sequestered in the total biomass (tree + bamboo plantation) in 4 ha dump = 53.03 t/ha x 4 ha = 212.12 tons.

Therefore, rate of CO_2 sequestration = [212.12 tons/4ha/3 yrs) = 17.68 tons of CO_2/ha/yr

Table 19: Litter accumulation and estimation of CO_2 sequestration in Damoda ecorestoration site 1. (Size of quadrate: 0.5m x 0.5 m and area of sampling= $0.25m^2$; date of study: 25.7.2015)

Sl no.	Location of litter collection	Fresh weight of litter (g)	Moisture free dry weight of litter (g)	Moisture content (%)	Dry weight of litter (kg)	Litter accumulated (kg/m2)	Litter accumulated (t/ha)
1	*Grass + B. arundanacea*	192	74	61.46	0.074	= 0.074/0.25 0.296	0.296 x 10 = 2.96
2	*Grass + B. arundanacea + D. sissoo*	207	78	62.32	0.078	0.312	3.12
3	*Grass + B. arundanacea*	253	116	54.15	0.116	0.464	4.64
4	*B. arundanacea*	42	18	57.14	0.018	0.072	0.72
5	*B. arundanacea*	40	20	50	0.02	0.080	0.80
						Average ± SD (Min- Max	**2.45±0.46 (0.72-4.64)**

1. Total Area of Damoda site 1 = 4 ha
2. Average litter accumulation in the ecorestoration site = 2.45 t/ha
3. Total carbon content in litter (assuming 40% carbon) = (2.45 x 0.4) = 0.98 tons/ha
4. CO_2 sequestered by litter (multiply factor of 3.67 with the carbon content) = (0.98 x 3.67) = **3.6 tons/ha**
5. CO_2 sequestered by litter accumulation/ ha/ year (assuming the age of reclamation is 3 yrs) = (3.59/3) = 1.20 tons/ha/yr

4.2.5 Analysis of minesoil properties

a) **Soil fraction % (<2mm size)** were analyzed to determine the percentage of the soil that supports the plants growth. Soil fraction at were estimated as 46.48% - 74.75% indicating high habitat heterogeneity. Estimated value of the soil fraction shows that site D-4, i.e., rhizosphere of *B. monosperma* tree supported by the higher percentage of the soil while soil fraction was found low where only Bamboo trees were planted (D-1). The average value of soil fraction for the entire sampling site (4 no) was 62 %. The distribution was mainly characterized by the plants roots and their rhozospheric functions. Similarly, course fraction were estimated at entire sampling site (D-1, D-2, D-3, and D-4) and found highest in D-1 site (53.22%) and found low at D-4 (24.25%), whereas the average value of course fraction at all the four site were 38% (**Table 20**).

b) **Soil paste pH (1:1 w/v)** were measured and found 6.78, 7.50, 6.95, and 7.85 for the site D-1, D-2, D-3, and D-4 respectively. Similarly, pH (1:2.5, w/v) were measured for all the four samples and found slightly higher as 6.89, 7.72, 7.03, and 8.01 for the site D-1, D-2, D-3, and D-4 respectively. pH of the mine soils mainly depend on the substrate and nature of the geological material of the earth crust.

c) **Electrical conductivity** is the measure of the ions present in the samples and mainly depends on the nature of the substrate and salts release by the plants root. At Damoda site-1 it is found highest in the D-1 site (0.26 dS/m) followed by the D-2 (0.18 dS/m), D-3 (0.18 dS/m), and lowest in D-4 (0.10dS/m) which is suitable for the plant growth. Moisture content was found highest in D-2 site (2.97%) due to the restriction of the water by the plain surface at the top of the dump site and may be due to the higher litter fall and followed by the D-1, D-3 and D-4 site.

d) **Soil organic carbon (SOC)** were estimated by the rapid dichromate method for all the four samples and found high in D-2 site (dump top) and followed by D-4 planted by *B. monosperma* (4.47%), D-1 which is planted by Bamboo species (3.97%) and D-3 which is planted by the *A. lebbeck* (3.32%).

Table 20: Physiochemical characteristics of soil samples collected from Damoda ecorestoration site 1 (Date of sampling: 12/03/15)

Soil parameters	D-1	D-2	D-3	D-4	Avg value ± SD (Min-Max) (CV%)
Soil fraction (<2mm size) %	46.78	66.74	59.33	74.75	61.90 ± 11.89 (46.78 - 74.75) (19.20)
Non-Soil fraction (>2mm size) %	53.22	33.26	40.67	24.25	38.10 ± 11.89 (24.25 - 53.22) (31.19)
pH (1:1)	6.78	7.50	6.95	7.85	7.27 ± 0.49 (6.78 - 7.85) (6.79)
pH (1:2.5)	6.89	7.72	7.03	8.01	7.41 ± 0.54 (6.89 - 8.01) (7.27)
EC(1:2.5) (dS/m)	0.26	0.18	0.10	0.18	0.18 ± 0.06 (0.10 - 0.26) (34.79)
Moisture content (%)	2.43	2.97	2.24	1.72	2.34 ± 0.51 (1.72 - 2.97) (21.94)
SOC (%)*	3.97	5.41	3.23	4.47	4.27 ± 0.91 (3.23 - 5.41) (21.40)
Av. N (mg/Kg)	84	96	110	88	94.50 ± 11.47 (84 - 110) (12.14)
Av-P (mg/Kg)	1.82	1.96	2.68	3.32	2.45 ± 0.69 (1.82 - 3.32) (28.40)

* By Walkley – Black (rapid dichromate digestion) method

e) **Plant available nitrogen** were found highest in the D-3 site (110 mg/kg), though *A. lebbeck* support nitrogen fixation and followed by the *D-2* (96 mg/kg), D-4 (88 mg/kg), and D-1 (84 mg/kg). The average value of the av. N of all the four site were estimated 94.50 mg/kg, which is suitable for the plant growth and also showed the nitrogen fixing potential of the various plant species found on the restored dump. Plant available phosphorus is the limiting factor for the plant growth, the estimated values of the average. P was found high in the D-4 site followed by the D-3, D-2 and D-1 sites.

f) **Total soil carbon (TSC)** analyzed for all the samples collected from Damoda ecorestoration site 1 after the sieving through <250 µ size was found in the range of 1.72 – 2.31 % and the average value was 2.01 %. (**Table 21**). After 1 M HCL treatment of the soil samples, IC % was analysed by CHNS analyzer; about 8% of TSC (average 0.17 % within a range of 0.14 – 0.20 %). Coal carbon % was determined by C fractionation method described by Ussiri et al. 2014. Average value of coal carbon was calculated as 0.87 % (about 43 % of TSC).The IC % and coal carbon % was substracted from the TSC to determine the organic portion, biogenic carbon which is used for CS calculation from minesoil. The quantity and quality of SOC (biogenic carbon) have strong influences on other essential soil characteristic such as cation exchange capacity (CEC), aggregation and water holding, nutrient accumulation and the soil's biochemical and microbial properties. It was found in the range of 0.84 - 1.08 % (average value of 0.98 %) Distribution of Total carbon (%), Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) of different mine soil samples at Tetulmari ecorestoration dump is shown in **Fig. 7.**

Table 21: Proportion of Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) present in the mine soil samples at Damoda old Ghutway ecorestoration site.

No. of samples	Total soil carbon (%)	Inorganic carbon (%)	Coal carbon (CC)%	Biogenic Carbon (BC) (%)
1	1.72	0.14	0.63	0.95
2	2.31	0.20	1.03	1.08
3	1.77	0.17	0.76	0.84
4	2.25	0.16	1.06	1.03
Avg ±SD (Min-Max)	**2.01 ± 0.31 (1.72-2.31)**	**0.17 ± 0.02 (0.14-0.20)**	**0.87 ± 0.21 (0.63-1.06)**	**0.98 ± 0.10 (0.84-1.08)**

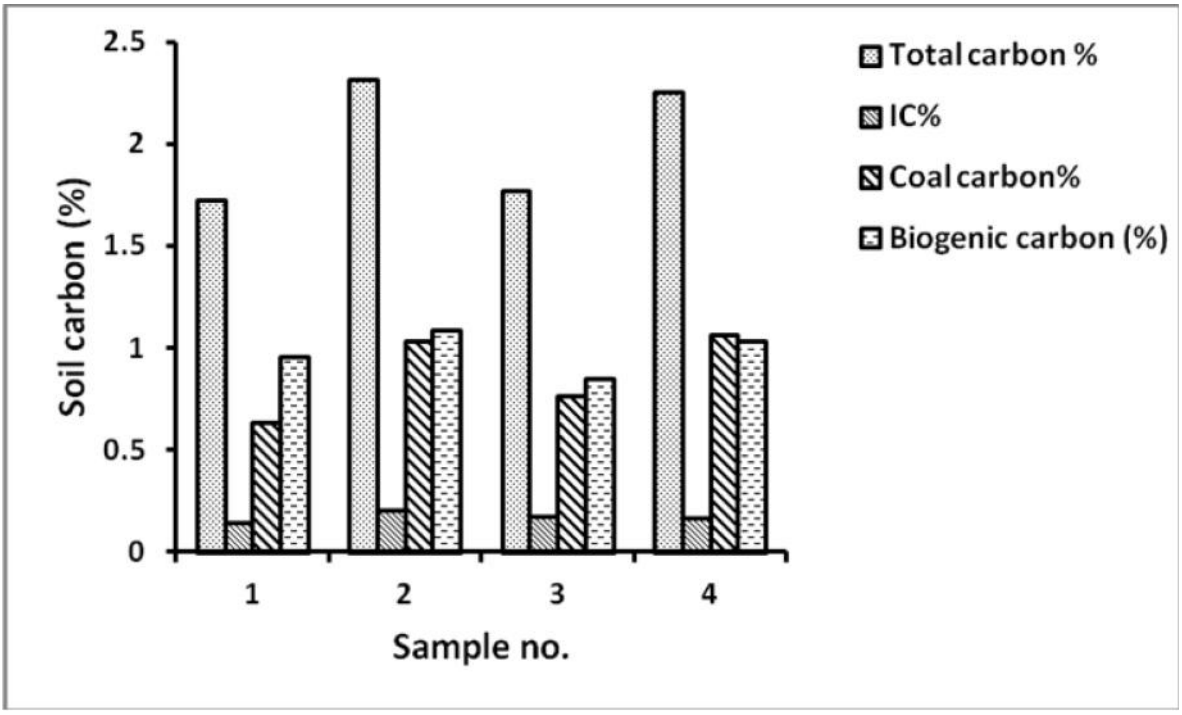

Figure 7: Distribution of Total carbon (%), Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) of different mine soil samples at Damoda old Ghutway ecorestoration site-1.

4.2.6 Estimation of the CO_2 sequestration of minesoil

Mining and associated disturbances disrupt the SOC equilibrium relationship, causing severe losses of SOC, leading to a C deficit of the natural soil. Mine soils possess very adverse conditions for both plant and microbial growth because of low organic matter contents and SOC, which is affected due to unfavorable physico-chemical characteristics, such as high pH, low cation exchange capacity (CEC), high bulk density and poor soil aggregate structure (high rock content). Revegetation and proper management practices help to regain the lost C; improve the soil quality and restore the SOC by reabsorbing it from the atmosphere. Thus the estimation of carbon sequestration is based on soil organic carbon (SOC) (%), bulk density (g/cc or t/m3) and depth (m) of soil. The SOC sequestration potential for RMS in mine soil samples at Damoda ecorestoration site 1 is estimated using the following equation (Lal et al., 1998):

$$\textbf{Mg C ha}^{-1} = [\%C * \text{Corrected } B_d * d\ (m) * 10^4\ m^2\ ha^{-1}] / 100$$

Where, Mg C ha^{-1} is Mega grams C per hectare (1 Mega gram =10^6 g = 1000 kg = 1 ton),

B_d (Mg m^{-3}) is the soil bulk density, (Mg/m^3 or t/m3 or g/cc) and d is the soil depth (m).

%C is the biogenic carbon calculated as discussed in section 3.7. Since the restoration site is young and still contains a considerable amount of coal carbon which mixes with the total soil carbon and interferes with the results of soil SOC and sequestration values, so only the biogenic portion is considered in sequestration study.

C-sequestration from minesoil of Damoda Ecorestoration site 1 was estimated as 16.33 t/ha on the basis of biogenic carbon, bulk density and depth whereas the CO_2 sequestered from the minesoil of the site was calculated as 59.93 t CO_2 /ha (**Table 22(a)**).

Table 22 (a): Estimation of CO_2 sequestration from soil samples at Damoda old Ghutway ecorestoration site 1 based on Biogenic Carbon (%), Bulk density (g/cc) and Depth (m) of soil.

No. of samples	Biogenic Carbon (BC) (%)	Corrected Bulk Density (g/cc or t/m3)	Depth (m)	C sequestered in mine soil* (t/ha)	CO_2 sequestered in mine soil** (t/ha)*
1	0.95	1.13	0.15	16.10	59.07
2	1.08	1.06	0.15	17.25	63.30
3	0.84	1.18	0.15	14.96	54.89
4	1.03	1.10	0.15	17.02	62.47
Avg ± SD (Min - Max)	**0.98 ± 0.10 (0.84 - 1.08)**	**1.12 ± 0.05 (1.02 - 1.16)**	**0.15**	**16.33 ± 1.04 (14.96 - 17.25)**	**59.93 ± 3.83 (54.89 – 63.30)**

***** calculated using Lal et al., 1998 equation:
C sequestered (t/ha) = [%C * Corrected B_d * d (m) *10^4 m^2 ha^{-1}] /100
****** CO_2 sequestered (t/ha) = C sequestered (t/ha) x 3.67

4.2.7 Estimation of total CO_2 sequestration for Damoda old Ghutway site-1

Total CO_2 sequestration of Damoda site-1 is estimated by calculating the C stock of (i) AGB of tree and bamboo plantation, (ii) litter & (iii) minesoil components. Next the C stock is converted to CO_2 equivalent (t of CO_2 sequestered/ha) & given in **Table 22 (b).**

Table 22 (b): Estimation of total CO_2 sequestration of Damoda ecorestoration site-1

Sl. no.	Different components of CO_2 sequestration	Total C stock (t/ha)	CO_2 sequestered (t/ha)
1	Aboveground & Belowground biomass	14.447	53.02
2	Litterfall	0.979	3.592
3	Soil	16.33	59.93
	Total	31.755	116.542

4.3 Damoda inclined Ghutway ecorestoration Site-2

4.3.1 Determination of Density and Relative Density of plant species

Two quadrates of size 10m x 10m were laid down in the site and species found is given in **Table 23a**. In 2 quadrate (equal to 200 m^2), 57 nos of trees were recorded, and *Dalbergia sissoo* (49%) and *Albizia lebbeck* (46%) together constitutes 95% of total plant population and the rest is contributed by *Azadirachta indica* (4%) and *Butea monosperma* (2%). The relative distribution of tree species in Damoda Ecorestoration Dump Site 2 is shown in **Figure 8 (a & b).** The tree density was calculated as 2850/ha and total no of trees in 3 ha of dump estimated 8,550 nos. The details of density of tree/ha, total estimated tree count, ecological frequency, frequency class, abundance and density of individual tree/ha is given in **Table 22a.** Total of 4 tree species and bamboo found during the quadrat survey was considered for the CS study

During the field survey, short heighted and mature tree species were found, from which number of saplings <1.5 heights (9 nos) were not considered for biomass estimation and CS study. During the quadrate survey, a total of 28 saplings were noted in 200 m^2 ha of the area **(Table 23b).** The no of saplings found in each quadrate varied from 11 to 17. Among the saplings, highest density was contributed by *D. sissoo* and *Albizia lebbeck* (25% each), *Butea monosperma* (18%) and *Acacia catechu (11%)* of the total plant density, followed by *Phyllanthus emblica* (7%) and rest by others (4%). Total nos of saplings were estimated as 1400nos. /ha and in 3ha, total saplings calculated as 4200 nos. Since maximum bamboo clumps dominated the vegetation in the area, 20 no of them were counted in the 2 quadrats studied. Therefore the density of bamboo clumps was calculated as 1000 clumps/ha; total clumps in 3 ha area of the dump was 3000 nos. A total of 21 nos of species were observed in the Damoda site-2, out of which 10 of them were found within the quadrat study including grass vegetation and shrubs and the rest were seen in other places of the site (**Table 24)**.

4.3.2 Measurement of Diameter at Breast Height (DBH) of tree species

Diameter at Breast Height (DBH) of tree species were measured for the estimation of above ground biomass (ABG) and root biomass of tree species by using allometric equation, which will be discuss in the section 2.2.6. DBH of all the 57 trees were measured by using Vernier caliper and measuring tape. Details of measurement of DBH are shown in **Table 25**.

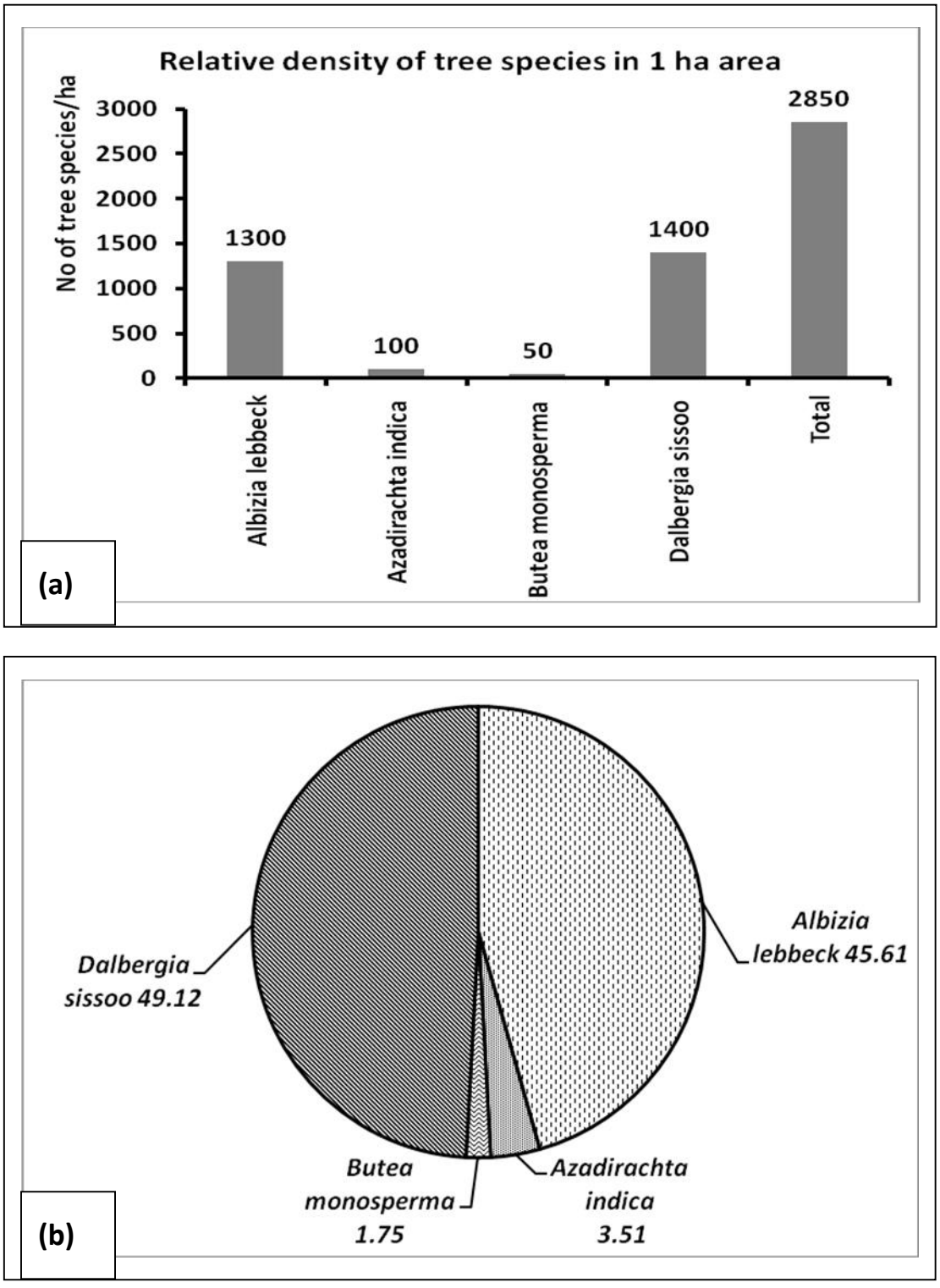

Figure 8 (a&b): Relative distribution of tree species in Damoda ecorestoration Site 2

Table 23(a): List of species recorded in quadrat of Damoda Inclined Ghutway Ecorestoration site 2, showing frequency (%), density (trees/ha), relative density and abundance. (Size of quadrat in this study: 10m x 10m=100m^2) (Date of sampling: 25.7.2015)

Sl no	Name of sp	Quadrats laid down		Total no of individual	Total no of quadrats of occurance	Total no of quadrats studied	Frequency (%)	Frequency class	Density (individual/unit area)	Density(per hectare)	Abundance	% of the total no of species
		1	**2**									
1	*Albizia lebbeck*	11	15	26	2	2	100.00	E	13.00	1300	13.00	46
2	*Azadirachta indica*	2	-	2	1	2	50.00	C	1.00	100	2	4
3	*Butea monosperma*	-	1	1	1	2	50.00	C	0.50	50	1	2
4	*Dalbergia sissoo*	16	12	28	2	2	100.00	E	14.00	1400	14.00	49
	Total=	29	28	57						**2850**		

No of trees in 200 m^2 = **57 nos.**

Density trees in the Damoda Ecologically Restored dump site 2 **=** (57/200)*10000 = **2850 trees/ha.**

Density of trees in total 3 ha area of Damoda Ecologically Restored dump site 2 **=** 2850 nos/ha * 3ha**=8550 nos.**

Table 23(b): List of saplings of height <1.5 m and Bamboo clumps observed in the quadrate of Damoda ecorestoration site 2. (Size of quadrat in this study: 10m x 10m=100m^2)

Sl no.	Tree species	Quadrates laid down		Total no of saplings	Relative Density (%)
		1	2		
1	*Aegle marmelos*	1	-	1	4
2	*Acacia catechu*	3	-	3	11
3	*Albizia lebbeck*	4	3	7	25
4	*Azadirachta indica*	1	-	1	4
5	***Bambusa arundanacea (clumps)***	**9**	**11**	**-**	**71**
6	*Bombax ceiba*	1	-	1	4
7	*Butea monosperma*	-	5	5	18
8	*Dalbergia sissoo*	5	2	7	25
9	*Phyllanthus emblica*	1	1	2	7
10	*Zizyphus mauritiana*	1	-	1	4
	Total =	26 [a]	22 [b]	**28** [c]	

[a] 17+ (Bamboo clumps-9);

[b] 11+ (Bamboo clumps-11);

[c] excluding 20 nos bamboo clumps

No of saplings in 200 m^2 = 28 nos. of <1.5 m saplings & 20 nos bamboo clumps

Hence, No of saplings in 1 ha= (28/200)*10000= 1400 nos of saplings/ha & (20/200)*10000 = 1000 nos of bamboo clumps /ha

So, Density of plantation:

(a) saplings in total 3 ha area of the site = 1400 saplings/ ha x 3 ha = **4200 nos of saplings**

(b) Bamboo in total 3 ha area of the site = 1000 x 3 = **3000 nos of bamboo clumps.**

Table 24: Type of Vegetation in Damoda Ecorestoration site 2

Sl no.	Type of plantation	Common name	Botanical name	Family
1	**Trees**	Sisham (Sissoo)	*Dalbergia sissoo*	Fabaceae
2		Neem (Margosa tree)	*Azadirachta indica*	Meliaceae
3		Bakain (Ghora neem)	*Melia azedarach*	Meliaceae
4		Pakur (Indian Tulip Tree)	*Ficus infectoria*	Moraceae
5		Karanj (Indian Beech)	*Pongamia pinnata*	Fabaceae
6		Kachnar (Kanchan)	*Bauhinia variegata*	Fabaceae
7		Kala Siris	*Albizia lebbeck*	Fabaceae
8		White Siris	*Albizia procera*	Fabaceae
9		Palash (Flame of the forest)	*Butea monosperma*	Fabaceae
10		Chatim (Indian devil tree)	*Alstonia scholaris*	Apocynaceae
11		Amla (Indian gooseberry)	*Phyllanthus emblica*	Phyllanthaceae
12		Semul (Red silk cotton tree)	*Bombax ceiba*	Malvaceae
13		Khair (Black catechu)	*Acacia catechu*	Mimosaceae
14		Semul (Red silk cotton tree)	*Bombax ceiba*	Malvaceae
15		Arjun	*Terminalia arjuna*	Combretaceae
16		Gamhar	*Gmelina arborea*	Lamiaceae
17		Peepal (Sacred Indian Fig tree)	*Ficus religiosa*	Moraceae
18		Bael (golden apple/stone apple)	*Aegle marmelos*	Rutaceae
19		Amaltas	*Cassia fistula*	Fabaceae
20		Indian almond	*Terminalia catappa*	Combretaceae
21	**Grasses**	Dennanath	*Pennisetum pedicellatum*	Poaceae
22		Kash	*Saccharam munja*	Poaceae
23		Kash	*Saccharam munja*	Poaceae
24		Kans	*Saccharam benghalense*	Poaceae
25		Kans	*Saccharam spontaneum*	Poaceae
26		Kash	*Saccharam munja*	Poaceae
27		Sui ghas	*Cenchrus ciliaris*	Poaceae
28		Dhaman grass	*Cenchrus setigerus*	Poaceae
30		Doob grass	*Cynodon dactylon*	Poaceae
31		Bamboo (Indian thorny bamboo)	*Bambusa arundanacea*	Poaceae
32	**Shrubs**	Ber (Indian plum)	*Ziziphus mauritiana*	Rhamnaceae
33	**Fruit trees**	Jamun	*Syzygium cumini*	Myrtaceae
34		Mango	*Mangifera indica*	Anacardiaceae
35		Guava	*Psidium guajava*	Myrtaceae

Table 25: Classification of tree species based on DBH at Damoda ecorestoration Site 2

Name of Tree species	Occurrence of species in Quadrat no.	Circumference (cm)	DBH(cm)**	No of trees in each quadrate (n)
Albizzia spp (n=26)	1	22	7.01	11
		20.2	6.43	
		21.6	6.88	
		18	5.73	
		14	4.46	
		12	3.82	
		18.5	5.89	
		19	6.05	
		20	6.37	
		15	4.78	
		17.5	5.57	
	2	18.2	5.80	15
		15	4.78	
		21	6.69	
		16.8	5.35	
		14	4.46	
		16.2	5.16	
		17	5.41	
		19	6.05	
		20.5	6.53	
		15.5	4.94	
		10	3.18	
		11.5	3.66	
		15	4.78	
		22	7.01	
		19.2	6.11	
Azadirachta indica (n=2)	1	11	3.50	2
		12	3.82	
Butea monosperma (n=1)	2	39	12.42	1
Dalbergia sissoo (n=28)	1	15	4.78	16
		14	4.46	
		18	5.73	
		17	5.41	
		20	6.37	
		32.5	10.35	

		16	5.10	
		18.2	5.80	
		20.5	6.53	
		22	7.01	
		21	6.69	
		13.4	4.27	
		16.6	5.29	
		18	5.73	
		18.5	5.89	
		14.3	4.55	
	2	35	11.15	12
		28	8.92	
		20	6.37	
		18.6	5.92	
		22	7.01	
		30	9.55	
		14	4.46	
		16	5.10	
		18	5.73	
		20.4	6.50	
		10.5	3.34	
		12	3.82	
			Total =	**57**

*n=Total no of tree species present.

**DBH (cm) = circumference (cm) / 3.14

4.3.3 Estimation of above ground biomass (AGB) and Root biomass (RB) and CO_2 sequestration

Table 26 depicts estimation of above ground biomass (AGB) and root biomass at Damoda inclined Ghutway ecorestoration site-2 based on DBH classes of individual tree species. Density of tree species used for CS study at the Damoda site-2 was 2850/ha. AGB and BGB of 4 tree species in the quadrat study were calculated by using allometric equation given by Brown (1997) using the average DBH of the tree species distributed among DBH classes. The AGB values were used for calculating BGB or RB by MacDicken (1997) equation Out of 4 tree species, *D. sissoo*, contributed maximum biomass; 14.48 t/ha AGB and 2.90 t/ha RB. Out of the 4 tree species in the quadrat, *D. sissoo* trees were classified into 5 BDH classes with DBH ranging from 3-5cm, 5-7cm, 7-9cm, 9-11cm and 11-13cm. Among these 5 DBH classes, a total of highest density of *D. sissoo, (*1400 nos. / ha) was calculated than the other tree species..

In **Table 27**, total estimation of above ground biomass (AGB) and BGB was done by adding up the AGB and BGB of all individual tree species (converting to t/ha). We have seen that the density of bamboo clumps is very high in this ecorestoration site. Hence, in this study carbon sequestration by bamboo plantation was calculated by considering the work of Singh and Singh (1999). Details of calculation of biomass of bamboo plantation and CO_2 sequestration from total biomass (tree + bamboo) is given in **section 3.5.1**.

The total tree biomass was estimated 32.01 t/ha and the corrected biomass of bamboo clumps was calculated as 2.6 t/ha. Thus the total biomass (tree and bamboo) was calculated as 34.61 t/ha. The aboveground live-biomass has significant contribution towards increase in C sequestration where mined sites have been reclaimed to forest. This contribution also depends on the type of forest and species. The ABG, BG, DBH and tree density in ecorestoration minesoil sites and natural forest in Indian conditions are given in **Table 28**.

The carbon stock of the tree and bamboo biomass of 34.61 t/ha is equal to 17.31 t/ha Next, the amount of CO_2 sequestered per hectare was calculated as 65.51 t of CO_2/ha. The CO_2 sequestered by the tree and bamboo biomass in4 ha area of the ecorestoration site at Damoda inclined Ghutway site-2 is calculated as 190.59 tons. Whereas, the rate of CO_2 sequestered at the site was calculated as 21.18 tons CO_2 /ha/yr.

Table 26: Estimation of above ground biomass (AGB) and root biomass (RB) based on DBH (Diameter at Breast height) class for individual tree species (no of trees/ha = 2850) at Damoda ecorestoration site 2.

Tree species name	DBH range (cm)	Avg DBH (cm)	No of trees in 200m^2	No of trees/ha [3]	AGB of each tree (kg)[1]	AGB of all trees (t/ha)	Root biomass (RB) (t/ha)[2]
Albizia lebbeck	3- 5	4.32	9	450**	4.04*	1.82#	0.36##
	5 - 7	6.00	15	750	8.69	6.51	1.30
	7 - 9	7.01	2	100	12.44	1.24	0.25
		Total	**26**	**1300**	**25.17**	**9.58**	**1.92**
Azadirachta indica	3- 5	3.66	2	100	2.76	0.28	0.06
		Total	**2**	**100**	**2.76**	**0.28**	**0.06**
Butea monosperma	11- 13	12.42	1	50	46.94	2.35	0.47
		Total	**1**	**50**	**46.94**	**2.35**	**0.47**
Dalbergia sissoo	3- 5	4.24	7	350	3.88	1.36	0.27
	5 - 7	5.88	15	750	8.27	6.20	1.24
	7 - 9	7.64	3	150	15.22	2.28	0.46
	9 - 11	9.95	2	100	28.08	2.81	0.56
	11- 13	11.15	1	50	36.52	1.83	0.37
		Total	**28**	**1400**	**91.96**	**14.48**	**2.90**

[1] **Above ground biomass (**AGB) of each tree was calculated by Brown (1997) equation:

Y (biomass in kg) = exp (-1.996 + 2.32 * ln DBH (cm));

= exp (-1.996 +2.32 * ln (4.32)) = 4.04 kg (*****)

[3]No of trees/ ha = (No. of trees in 200 m2 / 200 m2 area of quadrat) x 10000

****** (9/200) x 10000 = 450 no of trees / ha

[#]4.04 kg x 450 (no of trees/ha) x 10^{-3} (conversion factor of biomass; kg to tons) = 1.82 **t/ha**

[2] Root biomass, calculated by MacDicken (1997) formula = above ground biomass (t/ha) x 0.2

[##] 1.82 (t/ha) x 0.2 = 0.36 (t/ha)

Tree density/ha in the ecorestoration site (1300+100+50+1400) = **2850 trees/ha**

Table 27: Estimation of total aboveground biomass (AGB) and root biomass (RB) of tree and bamboo (tree density 2850 / ha) [by using Brown (1997) and MacDicken (1997) equation] and CO_2 sequestration at Damoda ecorestoration site 2

Tree species name	No of trees/ ha	Total AGB of tree species (t/ha)[1]	Total RB of tree species (t/ha)[2]	**Total biomass (AGB+RB) (t/ha)**
	A	b	c	d (b +c)
Albizia lebbeck	1300	9.58	1.92	11.49
Azadirachta indica	100	0.28	0.06	0.33
Butea monosperma	50	2.35	0.47	2.82
Dalbergia sissoo	1400	14.48	2.90	17.37
Total	2850	26.68	5.34	**32.01**

* All the values in column a, b and c obtained from **Table 26**

[1] Values calculated by Brown (1997) equation;

[2] Values calculated by MacDicken (1997) formula

Total tree biomass (above ground and root biomass) = **32.01 tons/ha**

Bamboo density (nos of clumps/ha)	Average biomass (t/ha)*	Corrected Biomass (tons/ha)**
1000	6.5	2.6

*Average biomass (t/ha) = density of bamboo x 0.006525 = 1000 bamboo shoots / ha x 0.0065 = 6.5 t/ha.

The factor 0.0065 is derived from Singh & Singh (1999) (26.1 t/ha / 4000 nos/ha = 0.0065).

Corrected Biomass (t/ha) = 40% of biomass is considered due to young age of bamboo plantation = 6.5 t/ha x 0.4 **= 2.6 tons/ha

Total biomass of tree and bamboo plantation = 32.01 + 2.6 = **34.61 t/ha**

Carbon stock of trees and bamboo = 34.61 t/ha x 0.5 (factor to convert amount of C fixed in the biomass) = **17.305 t/ha**

CO_2 sequestered = 17.31 t/ha x 3.67 (factor to convert C to CO_2) = **63.51 t/ha**.

CO_2 sequestered in the total biomass (tree + bamboo plantation) in 3 ha dump = 63.51 t/ha x 3 ha = 190.59 tons.

Therefore, rate of CO_2 sequestration = [190.59 tons/3ha/3 yrs) = 21.18 tons of CO_2/ha/yr

Table 28: Aboveground biomass (ABG), belowground (BG) biomass, DBH and tree density in ecorestoration minesoil sites and forest in Indian conditions.

Forest type/vegetation & Location and description of area	Tree species & Age of vegetation (years)	Quadrate size	Average DBH / DBH class (cm)	Tree density (trees/ha)	ABG biomass (t/ha)	BG biomass (t/ha)	Total biomass (t/ha)	Reference
Coal mine spoil land - Jayant opencast coal mine, Singrauli, India	*A. auriculiformis, C. siamea* (4 yr)	25m x 25m-	-	-	8-54.7	-	-	Dutta and Agarwal, 2003
Coal mine spoil land Jayant opencast coal mine, Singrauli, India	Bamboo 3 5	15m x 15m	-	45-47 clumps/plot	46.9 74.7	35% of ABG	-	Singh and Singh (1999)
Tarai Shisham forests - India	*D. sissoo* 5 10 15	50m x 50m	10-27 15-29 21-32	625	41.8- 78.6 103.1	-	58.7 106.1 136.1	Lodhiyal et al. (2002)
Bhabar Shisham forests - India	*D.sissoo* *5* *10* *15*	50m x 50m	9-19 13-25 19-28	625 625 625	35.1 60.3 89.8	-	-	Lodhiyal et al. (2003)
Terai Forest Uttarakhand, India	Mixed plantation of *D.sissoo, A. catechu & A. lebbeck (4 yrs)*		<10 cm	625	-	-	10.86	Singh et al. (2011)

4.3.4 Estimation of CO_2 sequestration in litter

The accumulation and decomposition of plant litter is one of the most important processes in the initiation of nutrient cycling for the establishment of a self sustaining ecosystem in the afforested mine degraded lands. The accumulation of plant litter depends on type of tree species, age of plantation, density and seasons, while decomposition depends on climatic conditions, soil moisture, microbial activity and physico-chemical properties of the mine soil. It has been reported that leaf litter disappears much faster than twigs and branches. Litter accumulation rate in the reclaimed coal mine overburden dumps and forest areas are give in **Table 29**.

Table 29: Litter fall rate in Indian forests and ecorestoration minesoil sites

Forest type/vegetation	Tree species	Age of vegetation (years)	Location and description of area	Size of Quadrate	Drying Temp of litter (^oC)	Litter fall rate (t/ha/yr)	Reference
Coal mine spoil land	*A. auriculiformis, C. siamea*	4	Jayant OCP, Singrauli,	-	80	1.2-3.6	Dutta and Agarwal, (2002)
Bamboo Savanna ecosystem	Bamboo	-	India	-	80	2.7-5.9	Tripathi and Singh (1995)
Coal mine spoil land	Bamboo	3-5	Jayant OCP Singrauli,	-	-	1	Singh and Singh (1999)
Dry deciduous Forest	-	-	India	-	-	1.0-6.2	Singh (1968)
Tarai Shisham forests	*D. sissoo*	5-15	India	50cm x 50cm	60	2.7-5.1	Lodhiyal et al. (2002)
Bhabar Shisham forests	*D.sissoo*	5 10 15	India	50cm x 50cm	60	2.28 3.61 4.37	Lodhiyal et al. (2003)
Terai Forest	Mixed plantation of *D.sissoo, A. catechu & A. lebbeck*	4	Uttarakhand, India	-	-	1.52	Singh et al. (2011)

In the present study, Litter accumulation underneath different trees and grasses were estimated. The average litter accumulation was found 2.73 t/ha in the present study so in total of 3 ha area litters accumulation is 8.19 tons **(Table 30).**

Total Carbon content in the litter was calculated by assuming 40% carbon content is in the litter and CO_2 sequestered by litter component amounts to 3.28 t/ha for a 3 year period (assuming the age of reclamation is 3 years). Therefore CO2 sequestered through the litter component in t/ha/yr is calculated as1.34 t/ha/yr.

Table 30: Litterl accumulation and estimation of CO_2 sequestration in Damoda ecorestoration site 2. (Size of quadrate: 0.5m x 0.5 m and area of sampling= $0.25m^2$; date of study: 25.7.2015)

Sl no.	Location of litter collection	Fresh weigh of litter (g)	Moisture free dry weight of litter (g)	Moisture content (%)	Dry weight of litter (kg)	Litter accumulated (kg/m^2)	Litter accumulated (t/ha)
1	*Grass + B. monosperma* leaves	156	56	64.10	0.056	0.056/0.25 = 0.224	0.224 x 10 = 2.24
2	*Grass + B. arundanacea*	225	86	61.78	0.086	0.344	3.44
3	*Grass + B. arundanacea*	184	63	65.76	0.063	0.252	2.52
						Average ± SD (Min- Max)	**2.73±0.63 (2.24-3.44)**

1. Total Area of Damoda ecorestoration site 2: 3 ha
2. Average litter accumulation in the ecorestoration site = 2.73 t/ha
3. Total carbon content in litter (assuming 40% carbon) = (2.73 x 0.4) = 1.092 tons
4. CO_2 sequestered by litter (multiply factor of 3.67, to convert C to CO_2) = (1.092 x 3.67) = **4.01 tons/ha.**
5. CO_2 sequestered by litter accumulation per ha / year (assuming the age of reclamation is 3 yrs) = 1.34 tons/ha/yr

4.3.5 Analysis of minesoil properties

a) **Soil fraction %** (<2mm size) were analyzed to determine the percentage of the soil that supports the plants growth. Average soil fraction at DII-1 were estimated 44.57%, at DII-2; 34.94%, at DII-3; 44.15%, and at DII-4; 32.38. Estimated value of the soil fraction shows that site DII-1 that is rhizosphere of bamboo tree supported by the higher percentage of the soil and at site DII-4 soil fraction was found low where only *D. sissoo* trees were planted. The average value of soil fraction for the entire sampling site (DII-1, DII-2, DII-3, and DII-4) was 39 %. The distribution was mainly characterized by the nature of the substrate, plants roots and their rhozospheric functions. Similarly, course fraction were estimated at entire sampling site (DII-1, DII-2, DII-3, and DII-4) and found highest in DII-4 site (67.62%) and found low at DII-3 (55.85%), whereas the average value of course fraction at all the four site were 61% **(Table 31).**

b) **Soil paste pH** (1:1 w/v) were measured by pH electrode and found 6.89, 7.50, 6.93, and 7.53 for the site DII-1, DII-2, DII-3, and DII-4 respectively. Similarly, pH (1:2.5, w/v) were measured for all the four samples and found slightly higher as 7.05, 7.07, 7.62 and 5.51 for the site DII-1, DII-2, DII-3, and DII-4 respectively. pH of the mine soils mainly depend on the substrate and nature of the geological material of the earth crust.

c) **Electrical conductivity** at Damoda site-2 found highest in the DII-3 site (0.21 dS/m) followed by the DII-2 (0.19 dS/m), DII-4 (0.19 dS/m), and lowest in DII-1 (0.12dS/m) which is suitable for the plant growth. EC is the measure of the ions present in the samples and mainly depends on the nature of the substrate and salts release by the plants root.

d) **Moisture content** was found highest in DII-3 site (4.47%) may be due to the higher litter fall and followed by the DII-2, DII-4 and DII-1 site.

e) **Soil organic carbon (SOC)** were estimated by the rapid dichromate method for all the four samples and found high in DII-2 site (*Albizzia* spp.) and followed by DII-4 planted by *D. sissoo* (3.75%), DII-3 which is planted by *Albizzia* spp.

(3.73%) and DII-1 which is planted by the *bamboo* (3.07%). The average SOC of all the four sampling site was estimated 4.13%.

f) **Plant available nitrogen** were found highest in the DII-1 site (112 mg/kg) and followed by the *DII-4* (96 mg/kg), DII-2 (84 mg/kg), and DII-3 (78 mg/kg). The average value of the av. N of all the four site were estimated 92.50 mg/kg, which is suitable for the plant growth and also showed the nitrogen fixing potential of the various plant species found on the restored dump.

g) **Plant available phosphorus** is the limiting factor for the plant growth, the estimated values of the available. P was found high in the DII-4 (3.25 mg/kg) site followed by the DII-1 (2.95 mg/kg), DII-3 (2.88 mg/kg) and DII-2 (2.25 mg/kg) sites **(Table 31).**

h) **Total soil carbon (TSC)** analyzed for all the samples collected from Damoda ecorestoration site 2 after the sieving through <250 µ size was found in the range of 1.34 – 1.72 % and the average value was 1.49 %. (**Table 31**). After 1 M HCL treatment of the soil samples, IC % was analysed by CHNS analyzer; about 9% of TSC (average 0.13 % within a range of 0.12 – 0.16 %). Coal carbon % was determined by C fractionation method described by Ussiri et al.(2014). Average value of coal carbon was calculated as 0.65 % (about 44 % of TSC). The IC % and coal carbon % was subtracted from the TSC to determine the organic portion, biogenic carbon which is used for CS calculation from minesoil. The quantity and quality of SOC (biogenic carbon) have strong influences on other essential soil characteristics such as cation exchange capacity (CEC), aggregation and water holding, nutrient accumulation and the soil's biochemical and microbial properties. It was found in the range of 0.61 – 0.80 % (average value of 0.71 %) Distribution of Total carbon (%), Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) of different mine soil samples at Damoda ecorestoration site 2 is shown in **Fig. 9**

Table 31: Physicochemical characteristics of soil samples collected from Damoda ecorestoration site 2 (Date of sampling: 12/03/15)

Soil parameters	DII-1	DII-2	DII-3	DII-4	Avg value ± SD (Min-Max) (CV%)
Soil fraction (<2mm size) %	44.57	34.94	44.15	32.38	39.01 ± 6.27 (32.38 - 44.57) (16.07)
Non-Soil fraction (>2mm size) %	56.30	65.06	55.85	67.62	61.21 ± 6.02 (55.85 - 67.62) (9.84)
pH (1:1)	6.89	6.93	7.53	5.27	6.66 ± 0.97 (5.27 - 7.53) (14.55)
pH (1:2.5)	7.05	7.07	7.62	5.51	6.81 ± 0.91 (5.51 - 7.62) (13.32)
EC(1:2.5)(dS/m)	0.12	0.19	0.21	0.19	0.18 ± 0.04 (0.12 - 0.21) (22.55)
Moisture content (%)	2.14	4.05	4.47	2.66	3.33 ± 1.11 (2.14 - 4.47) (33.36)
SOC (%)*	**3.07**	**5.97**	**3.73**	**3.75**	**4.13 ± 1.27 (3.07 - 5.97) (30.73)**
Av.N (mg/Kg)	112	84	78	96	92.50 ± 15.00 (78 - 112) (16.22)
Av-P(mg/Kg)	2.95	2.25	2.88	3.25	2.83 ± 0.42 (2.25 - 3.25) (14.83)

* By Walkley – Black (rapid dichromate digestion) method

Table 32: Proportion of Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) present in the mine soil samples at Damoda inclined Ghutway ecorestoration site 2.

No. of samples	Total soil carbon (%)	Inorganic carbon (%)	Coal carbon (CC)%	Biogenic Carbon (BC) (%)
1	1.34	0.12	0.61	0.61
2	1.72	0.16	0.79	0.77
3	1.35	0.12	0.58	0.65
4	1.55	0.13	0.62	0.80
Avg ± SD (Min - Max)	**1.49 ± 0.18 (1.34 – 1.72)**	**0.13 ± 0.02 (0.12 - 0.16)**	**0.65 ± 0.09 (0.58 – 0.79)**	**0.71 ± 0.09 (0.61 – 0.80)**

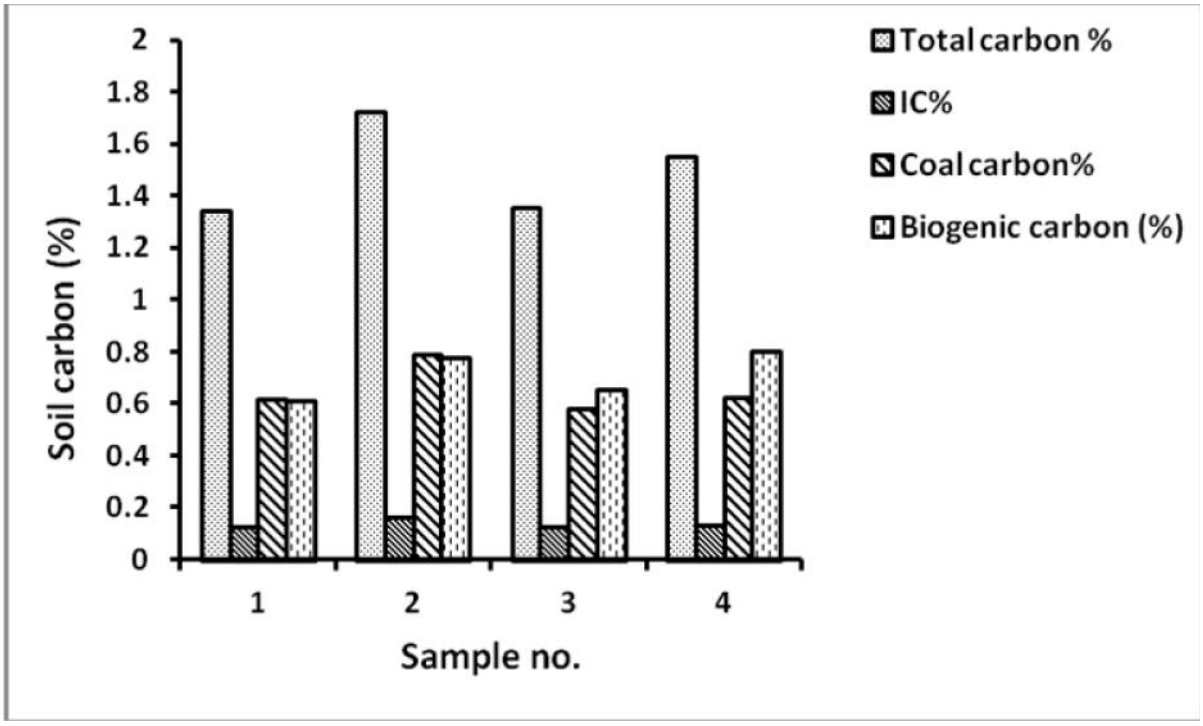

Figure 9: Distribution of Total carbon (%), Inorganic carbon (%), Coal carbon (%) and Biogenic carbon (%) of different mine soil samples at Damoda inclined Ghutway ecorestoration dump.

4.3.6 Estimation of the CO_2 sequestration of minesoil

Estimation of carbon sequestration in mine soil samples at Damoda ecorestoration site 2 was done based on biogenic portion of soil organic carbon (SOC) (%), bulk density (g/cc) and depth (m) of soil using the following equation (Lal et al., 1998):

$$\textbf{Mg C ha}^{-1} = [\%C * \text{Corrected } B_d * d\ (m) * 10^4\ m^2\ ha^{-1}] /100$$

Where, Mg C ha^{-1} is Mega grams C per hectare (1 Mega gram =10^6 g = 1000 kg = 1 ton),

B_d (Mg m^{-3}) is the corrected soil bulk density, (g/cc) and d is the soil depth (m).

%C is the biogenic carbon.

C-sequestration from minesoil of the Damoda ecorestoration site 2 was estimated 12.54 t/ha on the basis of biogenic carbon, bulk density and depth whereas the CO_2 sequestered from the minesoil of the site was calculated as 46.04 t/ha **(Table. 33(a)).**

Table 33(a): Estimation of CO_2 sequestration from soil samples at Damoda inclined Ghutway ecorestoration site 2 based on Biogenic Carbon (%), corrected Bulk density (g/cc) and Depth (m) of soil.

No. of samples	Biogenic Carbon (BC) (%)	Corrected Bulk Density (g/cc or t/m^3)	Depth (m)	C sequestered in mine soil (t/ha)	CO_2 sequestered in mine soil (t/ha)*
1	0.61	1.20	0.15	10.93	40.10
2	0.77	1.14	0.15	13.23	48.55
3	0.65	1.21	0.15	11.80	43.32
4	0.80	1.19	0.15	14.22	52.19
Avg ± SD (Min - Max)	**0.71 ± 0.09 (0.61 – 0.80)**	**1.19 ± 0.03 (1.14 - 1.21)**	**0.15**	**12.54 ± 1.47 (10.93 - 14.22)**	**46.04 ± 5.38 (40.10 - 52.19)**

4.3.6 Estimation of the CO_2 sequestration for Damoda inclined Ghutway site-2

Total CO_2 sequestration of Damoda inclined Ghutway site-2 is estimated by calculating the C stock of (i) AGB of tree and bamboo plantation, (ii) litter & (iii) minesoil components. Next the C stock is converted to CO_2 equivalent (t of CO_2 sequestered/ha) & given in T**able 33 (b).**

Table 33 (b): Estimation of total CO_2 sequestration of Damoda inclined Ghutway site-2

Sl.no.	Different components of CO_2 sequestration	Total C stock (t/ha)	CO_2 sequestered (t/ha)
1	Aboveground & Belowground biomass	38.73	142.15
2	Litterfall	1.508	5.533
3	Soil	17.89	65.65
	Total	58.128	213.33

4.4 Un-reclaimed coal mine overburden dump at Katras area and reference site (Reserve Forest site, Damoda area)

4.4.1 Analysis of un reclaimed dump and forest soil

The soil samples collected at un-reclaimed reclaimed coal mine overburden dump at Katras colliery area and natural forest site near Damoda colliery area were analysed by standard physicochemical methods (**Table 34**). These samples were analysed to compare the results with the properties of samples collected at the three ecorestoration sites as described in above sections. The soil organic matter value of soil was mainly used for comparision of carbon sequestration values calculated.

a) **Soil paste pH (1:1 w/v)** was measured by pH electrode and found 6.1 and 5.9 for the unreclaimed site and natural site respectively. Similarly, **pH (1:2.5, w/v)** were measured for all the samples collected and found slightly higher as 6.3 and 6.0 for both sites respectively. pH of natural forest was found to be acidic than found in restored sites as described in earlier sections due to clayey soil present and also due to the dominant vegetation found, i.e., Sal (*Shorea robusta*). The presence of this vegetation makes the soil acidic in nature. The mine soils mainly depend on the substrate and nature of the geological material of the earth crust.

b) **Electrical conductivity** was found in the range of 0.07 - 0.22 dS/m for unreclaimed site and 0.06-0.068 dS/m for the natural site. Moisture content was found higher than the ecorestoration sites (13%) since the sampling was done during monsoon season.

c) **Soil organic carbon (SOC)** were estimated by the rapid dichromate method for all the samples and found average of 3.4% and 2.02 % respectively for both the sites. Natural site had less value than the ecorestoration sites and un- reclaimed site due to absence of coal carbon as found in the reclaimed and unreclaimed dumps**.**

d) **Plant available nitrogen** in unreclaimed site was found less than the ecorestoration sites (average value of 58 mg/kg) but in natural forest site, it was found highest than the ecorestoration sites and unreclaimed site (average value of 128 mg/kg). However, the available nitrogen was in the natural reference forest was found close to the values of ecorestoration sites due to presence of sufficient vegetation in the restoration dumps and presence of dense grass vegetation.

e) Similar case was found for **plant available phosphorus**, which is the limiting factor for the plant growth. The estimated values of the available. P was found highest for natural site (10.9 mg/kg) than other ecorestoration or the unreclaimed site (6.24 mg/kg).

f) **Exchangeable K and Na** values were found suitable for plant growth.

g) **The exchangeable Ca and Mg** values were found higher for the un- reclaimed site (802 and 206 mg/kg) than the natural site (241 and 84 mg/kg).

h) **CEC** values were found suitable for plant growth within range 6.3-10.43 for unreclaimed mine site and 7.68-10.8 for the natural site.

i) **Base saturation** was also found higher for the un- reclaimed minesoil (average value of 62 %) than the natural forest site (average value was 27 %) (Table 31)

Table 34: Physico-chemical characteristics of minesoils of unreclaimed overburden dump (Katras area) (0-15cm depth) and control site (Reserve Forest, Damoda area) (0-15cm depth). (n=5).

Soil properties		Un-reclaimed mine soil Avg ± SD (Min - Max) (CV%)	Control site (Reserve forest) Avg ± SD (Min - Max) (CV%)
pH	(1:1;soil:water,w/v)	6.1 ± 0.3 (0.3 -6.4) (5.3)	5.9 ± 0.1 (0.1 - 5.9) (2.2)
	(1:2.5;soil:water,w/v)	6.3 ± 0.4 (5.8 - 6.7) (6.04)	6 ± 0.1 (5.9 - 6.2) (2.17)
EC(dS/m)	(1:2;Soil:water,w/v)	0.15 ± 0.07 (0.07 - 0.22) (44.47)	0.06 ± 0.001 (0.06 - 0.068) (5.00)
	(1:2.5;soil:water,w/v)	0.13 ± 0.06 (0.05 - 0.19) (44.85)	0.05 ± 0.003 (0.049 - 0.058) (6.08)
Moisture content (%)		13.29 ± 2.6 (10.7 - 16.7) (19.30)	13.29 ± 2.6 (14.37 - 16.35) (8.97)
Bulk density ($g/cm^{3)}$		1.6 ± 0.1 (1.4 - 1.7) (8.20)	1.6 ± 0.1 (1.2 - 1.48) (7.68)
SOC (%)		3.4 ± 0.7 (2.35 - 3.87) (19.89)	2.02 ± 0.2 (1.75 - 2.15) (10.59)
Av.N (mg/Kg)		58.72 ± 4.2 (54.4 - 64.2) 6.14	128.44± 4.0 (144.2 - 108.2) 5.16
Av-P(mg/Kg)		6.24 ± 1.3 (4.85 - 8.16) (21.01)	10.94± 0.4 (10.4 - 11.5) (3.86)
Ex-K (mg/Kg)		69.6 ± 13 (52 - 84) (18.11)	125 ±1.2 (124 - 127) (0.98)
Ex-Ca(mg/Kg)		802.8 ± 93 (680 - 938)(19.89)	241 ± 17 (222 - 260) (19.89)
Ex-Mg (mg/Kg)		206 ± 51 (160 - 280) (25.13)	84.1 ± 10 (72 - 98.7) (11.55)
Ex-Na (mg/Kg)		39.02 ± 10.4 (21.8 - 49.3) (21.01)	30 ± 4 (25 - 34.8) (13.70)
CEC (cmol/Kg)		9.7 ± 2.23 (6.3 - 10.43) (22.86)	8.6 ± 1.2 (7.68 - 10.8) (14.04))
Base saturation (%)		62 ± 13.20 (50.4 - 80.8) (21.07)	27 ± 3.57 (21.3 - 30.2) (13.25)

4.4.2 Estimation of the CO_2 sequestration of un-reclaimed minesoil forest soil

The C-sequestration potential of un-reclaimed reclaimed coal mine overburden dump at Katras colliery area and natural forest site near Damoda colliery area was calculated only for mine soil samples. C sequestration in mine soils systems occurs in aboveground biomass, i.e., stem, branch, and foliage, and in belowground biomass, i.e., roots, and in soil. However, the aboveground biomass and litterfall was not considered in this study since the sampling was done in monsoon season and quadrat sampling was difficult. There was only grass vegetation found in the un reclaimed site, hence there was no scope of litterfall or AGB. In this case we will consider the data found in literature for comparative study of C sequestration in our study.

Higher SOC found in natural site than mine soils systems; hence the SOC values were used for calculation of C sequestration in natural site which was considered free of coal carbon and inorganic carbon. However the Bulk density value used in calculation of CS for natural site is not the corrected one, since the soil consists of higher clay portion. Estimation of carbon sequestration in mine soil samples at Katras unreclaimed and forest site was based on soil organic carbon (SOC) (%), bulk density (g/cc or t/m3) and depth (m) of soil as calculated before (Lal et al., 1998).

It was found from the study that average C-sequestration potential of the unreclaimed minesoil at Katras was estimated as 7.86 t/ha (**Table 35**). Whereas in natural site, it was found much higher (35.5 t/ha) than the ecorestoration sites and also the unreclaimed site (**Table 36**) During the carbon fractionation, contribution by geogenic carbon in natural reference forest site was found negligible. The amount of CO_2 sequestered per hectare at the unreclaimed minesoil was calculated as 28.85 t of CO_2/ha, whereas in natural forest site, it was 130.58 t of CO_2/ha.

Table 35: Estimation of CO_2 sequestration in minesoil samples of unreclaimed overburden dump (Katras area) based on Biogenic Carbon (%), corrected Bulk density (g/cc) and Depth (m).

No. of samples	Total soil carbon (%)	Inorganic carbon (%)	Coal carbon (CC)%	Biogenic Carbon (BC) (%)	Corrected Bulk Density (g/cc)	Depth (m)	C sequestered in minesoil (t/ha)	CO_2 sequestered in minesoil (t/ha)
1	1.4	0.22	0.53	0.65	1.10	0.15	10.72	39.35
2	1.09	0.15	0.43	0.51	1.07	0.15	8.11	29.78
3	1.8	0.27	1.16	0.37	0.90	0.15	4.94	18.12
4	1.15	0.14	0.50	0.51	1.00	0.15	7.60	27.88
5	1.1	0.13	0.51	0.45	1.17	0.15	7.94	29.15
Avg±SD (Min-Max)	**1.31±0.30 (1.09–1.8)**	**0.18±0.06 (0.13-0.27)**	**0.63±0.30 (0.43-1.16)**	**0.50± 0.10 (0.37–0.65)**	**1.05± 0.10 (0.90-1.17)**	**0.15**	**7.86± 2.05 (4.94-10.72)**	**28.85 ± 7.54 (18.12-39.35)**

Table 36: Estimation of CO_2 sequestration in forest soil samples of control site (Forest near Damoda area) (0-15cm depth) based on Biogenic Carbon (%), Bulk density (g/cc) and Depth (m).

No. of samples	Biogenic Carbon (BC)[1] (%)	Bulk Density (g/cc or t/m3)	Depth (m)	C sequestered in soil (t/ha)	CO_2 sequestered in soil (t/ha)
1	2.2	1.20	0.15	39.6	145.33
2	1.7	1.40	0.15	35.7	131.02
3	1.9	1.30	0.15	37	135.79
4	1.5	1.48	0.15	33.3	122.21
5	1.7	1.27	0.15	32.3	118.54
Avg±SD (Min-Max)	**1.80 ± 0.26**	**1.33 ± 0.11**	**0.15**	**35.5 ± 2.9 (32.3-39.6)**	**130.29 ± 10.72 (118.54-145.33)**

[1] Total soil carbon in the reserve forest was estimated as 2.22 % and inorganic carbon was estimated as 0.18 %. During carbon fractionation, contribution by geogenic carbon was found negligible (0.24%).

4.5 Comparative analysis of CO2 sequestration of the ecorestoration sites, un-reclaimed dump and reference forest site

4.5.1 Estimation of total tree density

The total biomass of tree strands consist of above ground (shoot) biomass and root biomass, which was calculated by using allometric equations. Tree density of the three sampling sites were measured by using a quadrat and density was found as 1947 nos /ha in Tentulmari site to as high as 2850 nos/ha in Damoda – 2 site. These values are very higher because every year there may be additional plantations was carried out in these sites. Details of vegetation density, density of young saplings and bamboo vegetation is given in Table -37.

Table 37: Tree vegetation density (nos/ha), relative density of *Dalbergia sissoo* (%), density of tree saplings (nos/ha) and bamboo in the 3 ecorestoration sites.

Name of Ecorestored Site	Density of tree species (total no of trees/ ha)	Relative density of *Dalbergia sissoo* (dominant vegetation)	Density of total no of saplings/ ha (excluding bamboo)	Density of bamboo plantation/ ha	Total vegetation density (nos/ha)
Tetulmari	1947	66%	1359	147	3453
Damoda 1	2500	33%	1600	2033	6133
Damoda 2	2850	49%	1400	1000	5250

4.5.2 Estimation of total biomass (tree and bamboo)

Total biomass of tree species (above ground biomass, AGB + root biomass, RB) were calculated for the 3 ecorestored sites for the estimation of carbon sequestration (CS) which is presented in **Table 38.** Next, corrected final biomass (t/ha) of bamboo plantation is calculated (based on 40% of total biomass considered; total biomass calculated multiplying factor 0.0065 with density of bamboo plantation at the site; factor 0.0065 derived by considering the work of Singh and Singh (1999). Thus the total final biomass (trees and bamboo plantation) of each ecorestoration site is calculated by adding up the biomass of trees (t / ha) and corrected biomass of bamboo clumps (t/ha).

Table 38: Estimation of total biomass (tree & bamboo) in the 3 ecorestoration sites

Name of Ecorestoration sites	Total above ground biomass (AGB) of tree species (t/ha)	Total root biomass (RB) of tree species (t/ha)	Total biomass (AGB+RB) (t/ha)	Corrected biomass of bamboo clumps (t/ha)	Total biomass (tree+ bamboo) (t/ha)
Tetulmari	64.23	12.85	77.08	0.382	77.46
Damoda 1	19.68	3.94	23.61	5.28	28.89
Damoda 2	26.68	5.34	32.01	2.60	34.01

4.5.3 Calculation of CO_2 sequestration by total biomass (tree and bamboo)

The carbon sequestration by tree species and bamboo plantation for the all three sites was estimated after total biomass is calculated by assuming age of reclamation is 3 years. Highest value of CO_2 sequestration rate (tons/ha/yr) was observed in Tetulmari restoration site, because large no of old and mature *Dalbergia sisoo* plants were found growing in the dump. In other two dumps, CO_2 sequestration rate was observed to be low due to young age of plantation (**Table 39**).

Table 39: Calculation of C stock (t/ha) and CO_2 sequestration (ton/ha) in the three ecorestoration sites (assuming age of vegetation is 3 yrs).

Ecorestored Site name	Total biomass (tree + bamboo) (t/ha)	Total C stock (t/ha)	CO_2 sequestered (t/ha)
Tetulmari	77.46	77.46 x 0.5* = 38.73	38.73 x 3.67** = 142.15
Damoda 1	28.89	14.45	53.02
Damoda 2	34.01	17.31	63.51

* 0.5 is a factor to convert amount of C fixed in the biomass

** 3.67 is a factor to convert C to CO2

4.5.4 Estimation of CO_2 sequestration by litter

Average litterfall accumulated underneath different trees and grass species were calculated in t/ha for the three ecorestored sites and found to be 3.77, 2.45 and 2.73 t/ha respectively. These values were converted into carbon stocks and rate of carbon sequestration (CS) by the litter amount for three sites were calculated as 1.84, 1.20 and 1.34 t/ha/yr. Details of carbon sequestration calculation for each sites are given in **Table -40.**

Table 40: Estimation of litter accumulation and CO_2 sequestration in 3 ecorestoration sites (assuming age of vegetation is 3 years) (* 3.67 = a factor used for converting carbon (C) to CO_2.

Ecorestored Site name	Average Litter amount (t/ha)	Total C content (t/ha)	CO_2 sequestered by litter (t/ha)
Tetulmari	3.77± 0.41 (2.56 – 4.96)	3.77 x 0.4 = 1.508	1.508 x **3.67*** = 5.533
Damoda 1	2.45± 0.46 (0.72 – 4.64)	2.45 x 0.4 = 0.98	0.98 x 3.67 = 3.592
Damoda 2	2.73± 0.63 (2.24 – 3.44)	2.73 x 0.4 = 1.092	1.092 x 3.67 = 4.007

4.5.5 Analysis of physico-chemical properties of soil

Physicochemical parameters such as – soil fractions, pH (1:1, 1:2.5; w/v); electrical conductivity, bulk density, moisture content, soil organic carbon, available N, P, CEC, exchangeable cations, and base saturation were analyzed by standard methods (Maiti, 2013) and given in **Table - 41**.

Table 41: Physico-chemical characteristics of soil in ecorestoration sites, un-reclaimed dump and forest site.

Physicochemical characteristics	Tetulmari ecorestored dump	Damoda ecorestored dump site 1	Damoda ecorestored dump site 2	Un- reclaimed overburden dump	Reference Natural forest
Soil fraction (<2mm size) %	45.52 ± 7.97 (34.51 - 60.56)	61.90 ± 11.89 (46.78 - 74.75)	39.01 ± 6.27 (32.38 - 44.57)	25.6 ±3.4 (20.1-29.5)	80.6 ± 2.3 (75.3 – 87.4)
Non-Soil fraction (>2mm size) %	56.75 ± 5.75 (46.83 - 65.49)	38.10 ± 11.89 (24.25 - 53.22)	61.21 ± 6.02 (55.85 - 67.62)	74.4 ± 3.3 (70.4- 79.8)	19.4 ± 2.3 (13.2 – 25.4)
pH (1:1)	7.13 ± 0.70 (5.74 - 7.98)	7.27 ± 0.49 (6.78 - 7.85)	6.66 ± 0.97 (5.27 - 7.53)	6.1 ± 0.3 (0.3-6.4)	5.9 ± 0.1 (0.1-5.9)
pH (1:2.5)	7.24 ± 0.70 (5.91 - 8.01)	7.41 ± 0.54 (6.89 - 8.01)	6.81 ± 0.91 (5.51 - 7.62)	6.3 ± 0.4 (5.8-6.7)	6 ± 0.1 (5.9-6.2)
EC (1:2.5) (dS/m)	0.23 ± 0.07 (0.16 - .39)	0.18 ± 0.06 (0.10 - 0.26)	0.18 ± 0.04 (0.12 - 0.21)	0.13 ± 0.06 (0.05-0.19)	0.05 ± 0.003 (0.049-0.058)
Moisture content (%)	3.70 ± 1.09 (2.14 – 5.59)	2.34 ± 0.51 (1.72 - 2.97)	3.33 ± 1.11 (2.14 - 4.47)	13.29 ± 2.6 (10.7-16.7)	13.29 ± 2.6 (14.37-16.35)
SOC (%) *	4.85 ± 0.76 (3.67 - 6.12)	4.27 ± 0.91 (3.23 - 5.41)	4.13 ± 1.27 (3.07 - 5.97)	3.4 ± 0.7 (2.35-3.87)	2.02 ± 0.2 (1.75-2.15)
Av.N (mg/Kg)	96.78 ± 23.74 (69 - 128)	94.50 ± 11.47 (84 - 110)	92.50 ± 15.00 (78 - 112)	58.72± 4.2 (54.4-64.2)	128.44± 4.0 (144.2-108.2)
Av-P(mg/Kg)	2.14 ± 0.31 (1.87 - 2.86)	2.45 ± 0.69 (1.82 - 3.32)	2.83 ± 0.42 (2.25 - 3.25)	6.24± 1.3 (4.85-8.16))	10.94± 0.4 (10.4-11.5)

* By Walkley – Black (rapid dichromate digestion) method

Values are expressed in Average ± SD (Min-Max)

4.5.6 C stock and CO_2 sequestration in soil

The physicochemical parameters of soil samples collected from the ecorestored sites, un-reclaimed site and natural forest were analyzed by the standard methods. The soil C sequestered from soil organic matter in the 3 ecorestored sites, un-reclaimed overburden dump site at Katras colliery and a natural forest site near Katras was calculated using standard equation (**Table 42**).

Table 42: Estimation of C stock (t/ha) and CO_2 sequestration (t/ha) in soil of the 3 ecorestoration sites, un-reclaimed dump and forest site.

Name of Ecorestored Site	Total Soil Carbon (%)	Average Inorganic C (%)	Average Coal carbon (%)	Biogenic carbon (BC), %	Corrected Bulk Density, t/m3	Carbon sequestered (t/ha)	CO_2 sequestered (t/ha)
Tetulmari	2.36 ± 0.36	0.21 ± 0.03	1.07 ± 0.20	1.08 ± 0.14	1.11 ± 0.1	17.89 ± 1.67	65.65 ± 6.13
Damoda 1	2.01 ± 0.31	0.17 ± 0.02	0.87± 0.21	0.98 ± 0.10	1.12 ± 0.05	16.33 ± 1.04	59.93 ± 3.83
Damoda 2	1.49 ± 0.18	0.13 ± 0.02	0.65 ± 0.09	0.71 ± 0.09	1.19 ± 0.03	12.54 ± 1.47	46.04 ± 5.38
Unreclaimed dumps	1.31 ± 0.30	0.18 ± 0.06	0.63 ± 0.30	0.50 ± 0.10	1.05 ± 0.10	7.86 ± 2.05	28.85 ± 7.54
Reserve Forest (reference site)	2.22 ± 0.26	0.18 ± 0.12	0.24 ±0.15	1.80 ± 0.24	1.33 ± 0.11	35.5 ±2.90	130.29±10.7

*Biogenic carbon (%) = Total soil carbon (%) – (Inorganic C (%) + coal C (%))
** Assuming age of abundant of site = 6 yrs

4.5.7 Comparative analysis of CO_2 sequestration

A comparative study of carbon sequestration of at the ecorestoration sites (Tetulmari, Damoda site 1 and Damoda site 2) and unreclaimed dump and natural forest of Katras colliery area was done by adding up the C sequestered by all the components responsible for C sequestration. This was previously described in section 3.7 of methodology. **Table 43** describes the total values calculated for C sequestration from all components in all the sites in t/ha.

Table: 43 Comparative analysis of CO_2 sequestration of the 3 ecorestoration sites, unreclaimed dump and reference forest site.

Sl.no.	CO_2 sequestration by different components	Tetulmari Ecorestoration Site (age of the site 3 yr)	Damoda Ecorestoration Site 1(age of the site 3 yr)	Damoda Ecorestoration Site 2 (age of the site 3 yr)	Unreclaimed overburden dump	Natural forest site
1	Aboveground & Belowground biomass (t/ha)	142.15	53.02	63.51	17.63	242.587
2	Litterfall (t/ha)	5.533	3.592	4.007	1.145	5.650
3	Soil (t/ha)	65.65	59.93	46.00	28.85	130.285
	Total CO2 sequestration (t/ha)	213.33	116.542	113.517	47.625	378.522

The average total biomass reported for 10-15 years old shisham forest was in the range of 106 -136 t/ha (Lodhiyal et al., 2002), and total biomass assumed for the present study in the Reserve forest as 132.2 tons/ha. The corresponding carbon stock for 132.2 tons/ha calculated as 66.1 t C/ha and CO2 sequestration value estimated as 242.587 tons/ha. The CO2 sequestration in the litterfall component for the reference forest site estimated as 5.65 tons/ha, which is close to the Tetulmari ecorestoration site. However, CO_2 sequestration by soil was found highest in reserve forest (130.285 tons /ha) compared other sites.

In this study, CO_2 sequestration potential was found highest for Tetulmari site (213. 33t/ha) which is higher than Damoda ecorestoration site 1 (116.54 t/ha) and Damoda ecorestoration site 2 (113.52 t/ha).

Tripathi et al. (2014) compared the C sequestration rates of mine soil and forest ecosystem in US and Indian conditions. In US mine soil average CO_2 sequestration rates by soil C was 6.32 Mg ha^{-1} yr^{-1} in forest, while the potential CO_2 sequestration rate in forest ecosystem (include biomass, soil and litter) was 9.4 Mg $ha^{-1}yr^{-1}$. In Indian revegetated mine spoil, soil C sequestration rate was 20 Mg $ha^{-1}yr^{-1}$, while total C sequestration rate through soil, biomass and litter mass was 9.36 Mg ha^{-1} yr^{-1}. Total C sequestered in RMS is equivalent to 253.96 tonnes per ha (t ha^{-1}) capture of atmospheric CO_2 which indicates that mine spoil can act as a significant sink for atmospheric CO_2 through revegetation Thus total annual C budget was calculated as 8.40 t C $ha^{-1}yr^{-1}$ accumulation out of which 2.14 t ha^{-1} was allocated in above ground biomass, 0.31 t ha^{-1} in belowground biomass, 2.88 t ha^{-1} in litter mass and 1.35 t ha^{-1} in mine soil.

5.0 CONCLUSIONS AND RECOMMENDATIONS

1. Ecorestoration process is better alternative than sample plantation, because it leads to reinstatement of ecosystem in the degraded site. Due to development of 3-tier canopy over in the ecorestoration site, it not stabilizes and minimizes pollution but also these sites act as potential sink of CO_2. The accumulation of C stock will also be increased in biomass and minesoil components, with the gradual increase in age of ecorestoration, since these ecorestoration sites are very young (hardly 3 years old).
2. In coalmine ecorestoration sites, carbon sequestration can be estimated by adding C stock of 3 components; biomass, litterfall and soil organic matter. As these ecorestoration sites are very young (hardly 3 years old), the buildup of C stock is to its minimum, particularly in minesoil component. With gradual increase in age of ecorestoration, the accumulation of C stock will also be increased and maximum is expected in biomass component.
3. The overall CO_2 sequestered by all components in the three ecorestoration dumps was calculated as: Forest area (378 t CO2/ha)> . Tetulmari site (213 t CO2/ha) > Damoda old Ghutway (116 t CO2/ha) > Damoda inclined ghutway (113 t CO2/ha) > unreclaimed site (48 t CO_2/ha).
4. It is expected that, after 5 years, CO2 sequestration in Tetulmari will be in order of 350 t/ha and other sites in the range of 190-210 t/ha.
5. In two sites (Damoda old Ghutway and Damoda inclined Ghutway), the density of bamboo plantation was 1000-2000 per hectare and bamboo being a rapidly growing vegetation, it is expected that after 5-6 years, the biomass C stock will be substantiated.
6. The CO_2 sequestration in mine soil was found higher within the range of 46 t/ha (Damoda inclined Ghutway site -2) to 65.65 t/ha (Tetulmari ecorestoration site), but lower than the reference reserve forest site (130.29 t/ha).

6.0 FUTURE SCOPE OF WORK

1. The developing mine soils provide the better opportunity for the ecosystem management and can also increase the CO_2 Sequestration potential as compared to the other lands through adoption of proper restoration measure and integration of the ecological principles that support higher CO_2 Sequestration.

2. BCCL is the first company in the Coal Industry to conduct CO_2 Sequestration study. It is understood that BCCL is taking up Ecorestoration in 25 sites of about 226 ha and CO_2 Sequestration may be replicated at some other Ecorestoration sites of BCCL.

3. It is recommended that, as CO_2 Sequestration depends on nature of substrate, height and slope of the dump, geo-climatic condition of the area, type and age of vegetation, therefore, it should be done periodically in a span of 3 years for assessment of incremental rate of Carbon sequestration.

4. It is also recommended that other Coal companies and Mining industries may follow BCCL's model of three-tier Ecorestoration instead of simple plantation/ afforestation.

5. The findings of this study should be disseminated/made available to the Regulatory bodies, like MOEF& CC, MoC, CPCB, SPCBs and other Coal companies and Mining industries.

6. The report may also be displayed/ uploaded on BCCL websites/ Public domain.

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METHODS FOR ESTIMATING BIOMASS DENSITY FROM EXISTING DATA

This primer discusses two approaches for estimating the biomass density of woody formations based on existing forest inventory data. The first approach is based on the use of existing measured volume estimates (VOB per ha) converted to biomass density (t/ha) using a variety of "tools" (Brown et al. 1989, Brown and Iverson 1992, Brown and Lugo 1992, Gillespie et al. 1992). The second approach directly estimates biomass density using biomass regression equations. These regression equations are mathematical functions that relate oven-dry biomass per tree as a function of a single or a combination of tree dimensions. They are applied to stand tables or measurements of individual trees in stands or in lines (e.g., windbreaks, live fence posts, home gardens). The advantage of this second method is that it produces biomass estimates without having to make volume estimates, followed by application of expansion factors to account for non-inventoried tree components. The disadvantage is that a smaller number of inventories report stand tables to small diameter classes for all species. Thus, not all countries in the tropics are covered by these estimates. **To use either of these methods, the inventory must include all tree species.** There is no way to extrapolate from inventories that do not measure all species.

Use of forest inventory data overcomes many of the problems present in ecological studies. Data from forest inventories are generally more abundant and are collected from large sample areas (subnational to national level) using a planned sampling method designed to represent the population of interest. However, inventories are not without their problems. Typical problems include:

1. Inventories tend to be conducted in forests that are viewed as having commercial value, i.e., closed forests, with little regard to the open, drier forests or woodlands upon which so many people depend for non-industrial timber.
2. The minimum diameter of trees included in inventories is often greater than 10 cm and sometimes as large as 50 cm; this excludes smaller trees which can account for more than 30% of the biomass.
3. The maximum diameter class in stand tables is generally open-ended with trees greater than 80 cm in diameter often lumped into one class. The actual diameter distribution of these large trees significantly affects aboveground biomass density.
4. Not all tree species are included, only those perceived to have commercial value at the time of the inventory.
5. Inventory reports often leave out critical data, and in most cases, field measurements are not archived and are therefore lost.
6. The definition of inventoried volume is not always consistent.
7. Very little descriptive information is given about the actual condition of the forests, they are often described as primary, but diameter distributions and volumes suggest otherwise (e.g., Brown et al. 1991, 1994).
8. Many of the inventories are old, 1970s or earlier, and the forests may have disappeared or changed.

Despite the above problems, many inventories are very useful for estimating biomass density of forests. In the next two sections, details of the methods for using existing forest inventory data for biomass density estimation are presented.

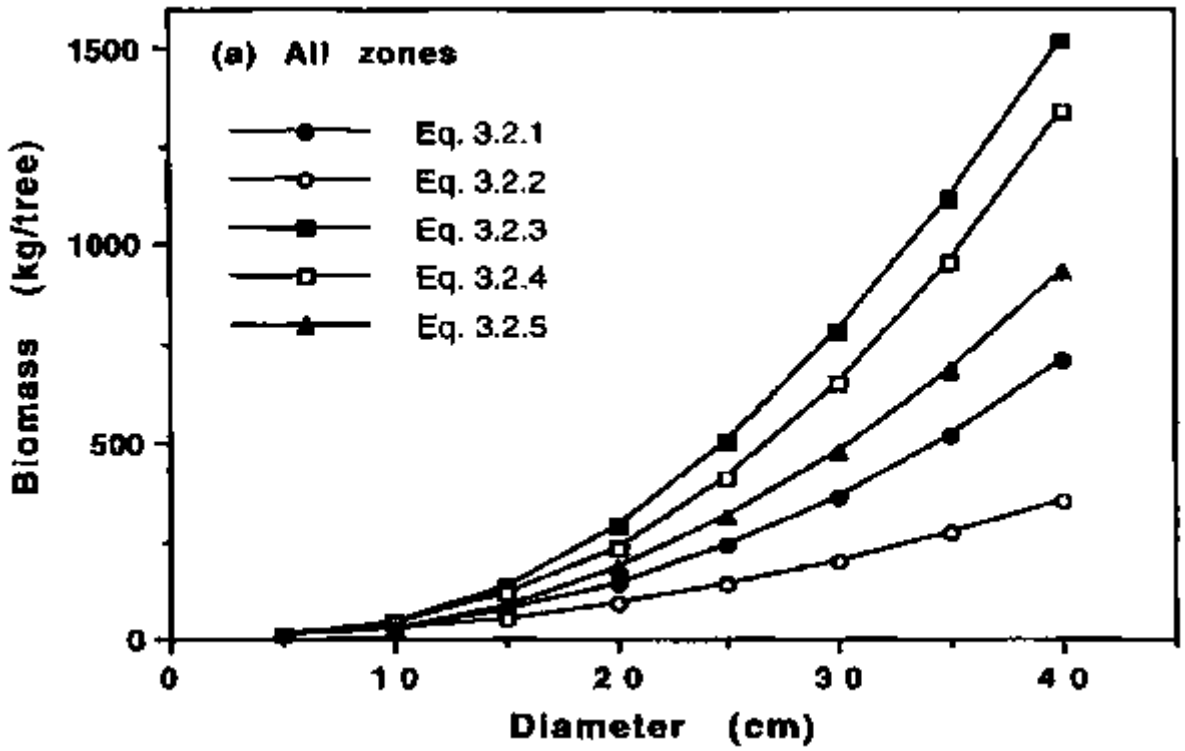
1.1 BIOMASS REGRESSION EQUATIONS

The biomass regression equations for broadleaf forests were developed from a data base that includes trees of many species harvested from forests from all three tropical regions (a total of 371 trees with a dbh ranging from 5 to 148 cm from ten different sources; see Appendix 2; equation 3.2.2 in the table below was developed by Martinez-Yrizar et al. (1992)). The biomass regression equations can provide estimates of biomass per tree. The data base was stratified into three main climatic zones, regardless of species: dry or where rainfall is considerably less than potential evapotranspiration (e.g. <1500 mm rain/year and a dry season of several months), moist or where rainfall approximately balances potential

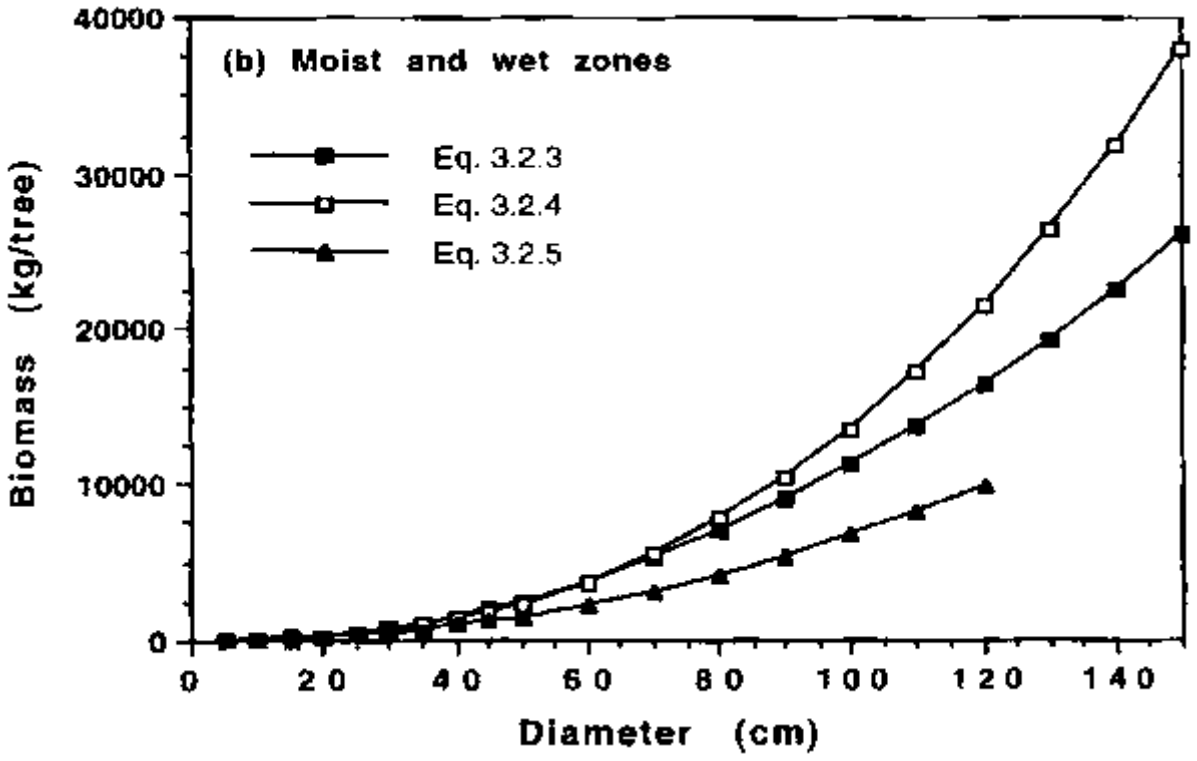
evapotranspiration (e.g. 1500-4000 mm rain/year and a short dry season to no dry season), and wet or where rainfall is in excess of potential evapotranspiration (e.g. >4000 mm rain/year and no dry season). These rainfall regimes are just guides, and generally apply to lowland conditions only. As elevation increases, as in mountainous areas, temperature decreases as does potential evapotranspiration and the climate zone becomes wetter at a given rainfall. For instance, an annual rainfall of 1200 mm in the lowlands would be the dry zone, but at about 2500 m it would be the wet zone. Therefore, judgement should be used in selecting the appropriate equation.

Figure 1 - Relationship between oven-dry biomass of tropical trees and dbh for (a) biomass regression equations by all climatic zones and trees with dbh between 5 to 40 cm, and (b) equations for moist and wet zones for trees in the full range of dbh. The equations are given in Section 3.2.1.

(a) All zones



(b) Moist and wet zones



- Biomass regression equations for estimating biomass of tropical trees. Y= biomass per tree in kg, D = dbh in cm, and BA = basal area in cm^2

Equation Number	Climatic zone	Equation	Range in dbh *(cm)*	Number of trees	Adjusted r^2
3.2.1	**DRY** [a]	**Y = exp{-1.996+2.32*ln(D)}**	**5-40**	**28**	**0.89**
3.2.2		Y =10^{-0.535+$\log_{10}$ (BA)}	3-30	191	0.94
3.2.3	MOIST [b]	Y = 42.69-12.800(D)+1.242(D^2)	5-148	170	0,84
3.2.4		Y = exp{-2.134+2.530*ln(D)}			0.97

None of the regression equations should be used for estimating the biomass of trees whose diameter greatly exceeds the range of the original data.

[a] Eq. 3.2.1 revised from Brown et al. (1989) for dry forest in India, and Eq. 3.2.2 from Martinez-Yrizar et al. 1992 for dry forest in Mexico (original equation based on BA). For dry zones with rainfall less than 900 mm/year use equation 3.2.2 and for dry zones with rainfall > 900 mm/year use equation 3.2.1. "exp" means "e to the power of".

[b] Both equations are based on the same data base; A. J. R. Gillespie, pers. comm. based on a revision of equation in Brown et al. (1989).

Analysis of the data bases implied that the trees within the dry and wet zones could be grouped together within a zone (Brown et al. 1989). Within the moist zone, the analysis indicated that different data bases were not statistically homogeneous and theoretically could not be grouped. For practical purposes, however, the moist zone was considered to be the population of interest and the different data bases were considered to be subsamples from this population. Thus a combined regression for the pooled data sets was developed (Brown et al. 1989).

Biomass regression equations for several species of pines combined into one data base was also developed. A simple method for estimating the biomass of palms was also developed (Frangi and Lugo 1985).

It is important that the biomass of trees with large dbh be estimated as accurately as possible because their contribution to the biomass of a forest stand is much more than their number suggests. For example, in mature moist tropical forests, the biomass in trees of dbh greater than 70 cm can account for as much as 40% of the stand's biomass density, although the number of these trees corresponds to less than 5% of all trees (Brown and Lugo 1992, Brown 1996).

The regression equation for trees in the wet zone (Eq. 3.2.5) matches the original data well and behaves well at larger diameters. As with the moist equation however, caution should be taken in using the equation much beyond the original data.

For most situations where an estimate of the biomass density of pine forests is needed, Eq. 3.2.8 can be used. However, if time and resources are available, a local biomass regression equation should be developed.

Below is an example of how to use the biomass regression equations with stand tables. The stand table example is for a moist forest in Ghana. Biomass density of this forest was estimated using the moist equation, Eq. 3.2.3. Maximum diameters are at about the upper limit for this equation (about 150 cm).

Use if the biomass regression equation, an example

Diameter class *(cm)*						
5-20	**20-40**	**40-60**	**60-90**	**90-120**	**120-150**	**>150**
1. Number trees/ha						
794	161	25.2	12.3	3.3	1.05	0.23
2. Mid-point of class, cm [a]						
12.5	30	50	75	105	135	155 [b]
3. Biomass of tree at mid-point of class using Eq. 3.2.3; kg						
70.5	646	2353	6563	15375	29038	41 187
4. Biomass of all trees, t/ha = (product of rows 1 and 3)/1000°						
56	104	59.3	80.7	50.8	30.5	9.5
Total aboveground biomass = sum of row 4 = 391 t/ha						

[a] As no additional information was available the mid-point of the diameter class was assumed to represent the class; as the classes are wide this could overestimate the biomass density estimate.

[b] Assumed to be diameter of largest class; choice of this upper limit when no additional data are present is problematic (see section 3.2.4).

[c] To convert kg to t

Although the approach presented here has emphasized the use of regression equations with stand tables, the regression equations can also be used with individual tree measurements from stands. Using individual tree measurements overcomes the problem of choosing the diameter of the class.

1.2 PROBLEMS WITH REGRESSION APPROACH

Several problems exist with this method, namely: (1) the small number of large diameter trees used in the regression equations (e.g., for the moist equation, the largest dbh was 148 cm, with only five trees >100 cm diameter), (2) the open-ended nature of the large diameter classes of the stand tables, (3) wide and often uneven-width diameter classes, (4) selection of the appropriate average diameter to represent a

diameter class, and (5) missing smaller diameter classes (i.e., incomplete stand tables to minimum diameter of 10 cm). To overcome the potential problem of the lack of large trees (problem 1), equations were selected that were expected to behave reasonably up to 150 cm or so or upon extrapolation somewhat beyond this limit (Brown et al. 1989). Rarely are stand tables encountered that contain trees much larger than the maximum dbh used in the regression.

The problem with open-ended large diameter classes is knowing what diameter to assign to that class. Sometimes additional information is included that educated estimates can be made, but this is often not the case. Clearly, further improvements in reporting the distribution of the largest diameter trees in stand tables would improve the reliability of the biomass density estimates as it is often these large trees that account for significant proportions of the total biomass density (Brown and Lugo 1992, Brown 1995). In the above example, the approximately 1.3 trees greater than 120 cm constitute about 70% of the biomass represented by the 794 trees in the smallest class.

Many inventories often report stand tables with wide and/or uneven-width classes. The most unbiased biomass density estimate is obtained when diameter classes are small, about 10 cm wide or smaller, and are even-width for the whole stand table. This problem is illustrated by the following example for a moist forest where in Example A the classes are 10 cm wide and in Example B two classes are combined to make them 20 cm wide.

Example A

Diameter class (cm)											
10-19	**20-29**	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80-89**	**90-99**	**100-109**	**110-119**	**>120**
Number of stems/ha											
183	80	35.1	11.8	4.7	2.3	1.5	0.9	0.5	0.4	0.2	0.5
Biomass/tree (kg) at mid-point of class(Eq. 3.2.3)											
112	407	954	1 802	2995	4570	6563	9008	11936	15375	19354	23900
Biomass of trees (product of rows 1 and 2), t/ha											
20.5	32.6	33.5	21.3	14.1	10.5	9.8	8.1	6.0	6.2	3.9	12.0
Total biomass density =178 t/ha											

Example B

Diameter class (cm)					
10-29	**30-49**	**50-69**	**70-89**	**90-109**	**>110**
1. Number of stems/ha					
263	46.9	7.0	2.4	0.9	0.7
2. Biomass/tree (kg) at mid-point of class(Eq. 3.2.3)					
232	1 338	3732	7727	13590	21 555
3. Biomass of trees (product of rows 1 and 2), t/ha					
60.9	62.7	26.1	18.5	12.2	15.1
Total biomass density =196 t/ha					

The biomass density in Example B, based on the 20 cm wide classes, is about 10% higher than that in Example A, based on the 10 cm wide class. In general, wider classes will overestimate the biomass density. However, regular estimation of biomass density as part of inventory analysis or accessibility to the field data should not encounter these problems because original inventory data generally includes details down to individual trees. Estimating the biomass of individual trees in inventory plots directly would overcome problems (2) to (4) given above. Foresters have wide experience in these type of calculations as they are basically no different from estimating volumes from volume equations.

To overcome the problem of incomplete stand tables, an approach has been developed for estimating the number of trees in smaller diameter classes based on number of trees in larger classes (Gillespie et al. 1992). It is recommended that the method described here be used for estimating the number of trees in one to two small classes only to complete a stand table to a minimum diameter of 10 cm. It is also emphasized that this method should only be used when no other data for biomass estimation are available.

The method is based on the concept that uneven-aged forest stands have a characteristic exponential or "inverse J-shaped" diameter distribution. These distributions have a large number of trees in the small classes and gradually decreasing numbers in medium to large classes. Pull details of the theory behind the approach and of the different methods tested are given in Gillespie et al. (1992). The best method was the one that estimated the number of trees in the missing smallest class as the ratio of the number of trees in dbh class 1 (the smallest reported class) to the number in dbh class 2 (the next smallest class) times the number in dbh class 1. This method is demonstrated in the following example:

1 Assume that: the minimum diameter class is 20-30 cm and we wish to estimate the number of trees in the 10-20 cm class.

2 The number of trees in the 20-30 cm class equals 80, and the number in the 30-40 cm class equals 35.

3 The estimated number of trees in the 10-20 cm class is the number in the 20-30 cm class x (number in 20-30/number in 30-40); this equals 80 x (80/35) =183.

To use this approach, diameter classes must be of uniform width, preferably no wider than 10-15 cm, and should not be used for estimating numbers of trees in more than two "missing' classes.

1.3 BIOMASS ESTIMATES OF INDIVIDUAL

The regression equations reported above can be applied to inventories of individual trees planted in lines, as living fence posts, for dune stabilization, for fuelwood, etc. Biomass estimates for individual trees are particularly useful in drier regions where the trees are grown for all the aforementioned products and services. However, as discussed above, the regression equations for dry zone trees are based on a small data base. Furthermore, trees grown in lines or in more open conditions generally display different branching patterns and are likely to have more biomass for a given diameter than a similar diameter tree grown in a stand. Although the above regression equations could be used where no other data exist for rough approximations, new regression equations need to be developed for trees growing in open conditions.

Assessment of biomass and carbon stock in present land use

Biomass is defined here as the total amount of live organic matter and inert organic matter (IOM) aboveground and belowground expressed in tonnes of dry matter per unit area (individual plant, hectare, region or country). Typically, the terms of measurement are density of biomass expressed as mass per unit area, e.g. tonnes per hectare. The total biomass for a region or a country is obtained by upscaling or aggregation of the density of the biomass at the minimum area measured.

BIOMASS is defined here as the total amount of live and inert organic matter above and below ground expressed in tons of dry matter per unit area.

FIGURE 1 - Quadrat sampling for biomass, biodiversity and land degradation assessments

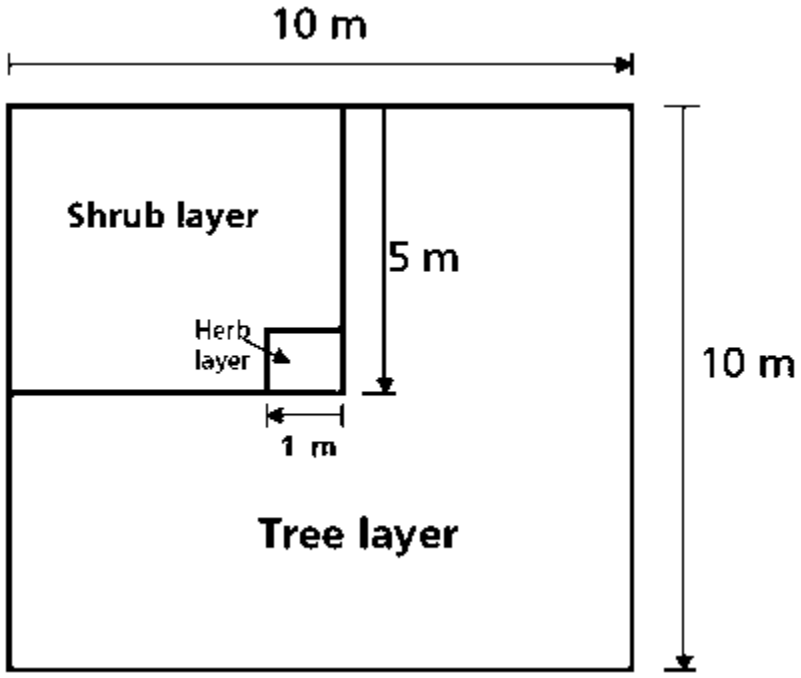


TABLE 1 - Use of each nested quadrat site for sampling and measurement

QUADRAT DIMENSIONS	USE OF QUADRAT IN MEASUREMENTS AND SAMPLING
10 × 10 m	Morphometric measurements of the tree layer.
	Measurements of trunk and canopy of trees and large deadwood.
	Identification of tree species and individual organisms within a species for biodiversity assessment.
	Site measurements and observations for land degradation assessment.
5 × 5 m	Study of the shrub layer.
	Morphometric measurements of the shrub layer.
	Measurements of stem and canopy and small deadwood.
	Identification of shrub species and individual shrub organisms within species for biodiversity assessment.
1 × 1 m	Sampling of biomass of herbaceous species and grasses, above- ground and roots, litterfall and debris for drying and weighing to determine live and dead biomass.
	Counting of herbaceous species and number of individuals within species.

The design of nested quadrats of different sizes (Figure4) obeys requirements for measuring and counting vegetation of different sizes and strata, and for collecting debris and litter for estimation of biomass. Table1 indicates the designated use for eachquadrat.

Calculation of aboveground biomass from allometric methods

The aboveground biomass is estimated from the field measurements at specific sites (quadrats) with which the landscape was sampled in the area or watershed of concern. These are described above. Here, the procedural steps for the calculation of aboveground biomass from such field data are described.

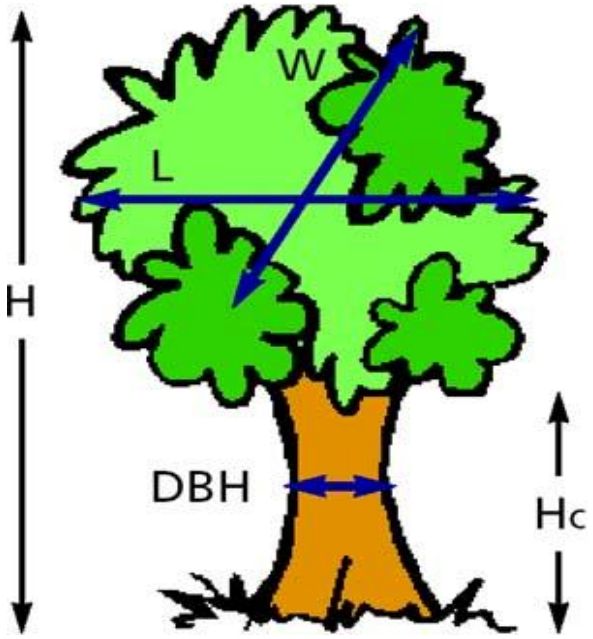
In order to be able to calculate aboveground biomass in a watershed, the following steps concentrate on the forest layers. For methodological convenience, the calculations of trees and shrubs are divided in two sections according to tree morphology:

- calculation of biomass for trunk or stem;
- calculation of biomass for canopy or crown.

This distinction is necessary because different procedures and approaches for estimation are used in each case. In each quadrat of 10 × 10 m the following allometric measurements are obtained from field sampling of each tree within the quadrat boundaries (Figure 6):

- tree height (H),
- diameter at breast height (DBH),
- diameter of canopy or crown in two perpendicular directions, termed here for convenience “length” (L) and “width” (W),
- height to the base of the crown (Hc),
- percentage of foliage cover in the crown or canopy (Fc).

FIGURE 2 - Allometric measurements in forest vegetation within the sampling quadrat,10 × 10 m



Here, two options are presented in terms of approaches to calculating trunk and canopy biomass. The selection of the approach depends to a large extent on the conditions and tools available during data collection, and therefore on the variables measured and the degree of accuracy required. The two approaches are:

- the allometric method,
- the linear regression equations method.

With the allometric method, consideration must be first given to the basal area (*Ab*) of the trunk. Where this has been recorded with conventional forest inventory equipment, the section below should be disregarded. Where the basal area has not been measured in the field, it can be estimated by:

$$A_b = \mathrm{P} \times r^2$$

where: P= 3.1415927; and *r* is the radius of the tree at breast height (0.5 DBH).

With A_b, the volume (*V*) in cubic metres can be calculated from:

$$V = A_b \times H \times Kc$$

where: A_b is the basal area; *H* is the height; and *Kc* is a site-dependent constant in standard cubing practice used in forest inventory (e.g. in Texcoco, *Kc* = 0.5463).

Using the calculated volume of the trunk, total trunk biomass in kilograms may be calculated by multiplying by the wood density (*WD*) corresponding to each tree species measured:

$$\text{Biomass} = V \times WD \times 1\,000$$

The linear regression equation approach requires the selection of the regression equation that is best adapted to the conditions in the study area. Linear regression models have been fitted to data in various situations of variable site and ecological conditions globally. The work done by Brown, Gillespie and Lugo (1989) and FAO (1997) on estimation of biomass of tropical forests using regression equations of biomass as a function of DBH is central to the use of this approach. Some of the equations reported by Brown, Gillespie and Lugo (1989) have become standard practice because of their wide applicability. Table 2 presents a summary of the equations, as found in the specialized literature, including the restrictions placed on each method.

TABLE 2: Estimation of biomass of tropical forests using regression equations of biomass as a function of DBH

AUTHOR	EQUATION	Restrictions: DBH and climate based on annual rainfall
FAO	(FAO-1) $Y = \exp\{-1.996 + 2.32 \times \ln(DBH)\}$ $R^2 = 0.89$	5 < DBH < 40 cm Dry transition to moist (rainfall > 900 mm)
FAO	(FAO-2) $Y = 10\ \wedge\ (-0.535 + \log10\ (p \times r^2))$ $R^2 = 0.94$	3 < DBH < 30 cm Dry (rainfall < 900 mm)
FAO	(FAO-3) $Y = \exp\{-2.134 + 2.530 \times \ln (DBH)\}$ $R^2 = 0.97$	DBH < 80 cm Moist (1 500 < rainfall < 4 000 mm)
Winrock (from Brown, Gillespie and Lugo, 1989)	(Winrock-1) $Y = 34.4703 - 8.0671\ DBH + 0.6589\ DBH^2$ $R^2 = 0.67$	DBH ³ 5 cm Dry (rainfall < 1 500 mm)
Winrock (from Brown, Gillespie and Lugo, 1989)	(Winrock-DH) $Y = \exp\{-3.1141 + 0.9719 \times \ln[(DBH^2)H]\}$ $R^2 = 0.97$	DBH > 5 cm Moist (1 500 < rainfall < 4 000 mm)
Winrock (from Brown Gillespie and Lugo, 1989)	(Winrock-DHS) $Y = \exp\{-2.4090 + 0.9522 \times \ln[(DBH^2)HS]\}$; $R^2 = 0.99$	DBH > 5 cm Moist (1 500 < rainfall < 4 000 mm)
Luckman	$Y = (0.0899\ ((DBH^2)^{0.9522}) \times (H^{0.9522}) \times (S^{0.9522}))$	Not specified

Note: p = 3.1415927; *r* = radius (cm); DBH = diameter at breast height (cm); *H* = height (m); BA = J × r^2; and *S* = wood density (0.61).

Using any of these methods, tree biomass can be estimated by applying the corresponding regression equation. Plots of tree biomass estimates by DBH using the various regression equations for different types of cover type can be generated to illustrate the variations in predictions from each of the regression equations listed in Table 2.

Where only the biomass of the trunk has been estimated (e.g. by allometric calculations), the biomass of the crown (canopy) will need to be estimated and added to the biomass of the trunk. The first step is to estimate the volume occupied by the canopy. Given the variability of shapes of tree crowns from one species to another and even intraspecific variations from one individual tree to another, some generalizations need to be made for estimation purposes in regard to the variations in canopy density given by the aerial distribution of the branches and their foliage. The methods used represent reasonable approximations under the current practical circumstances of estimation. The crown or canopy volume can then be estimated by a function depending on the geometrical properties of the shape of the crown, as indicated in Table 3.

The volume of the crown estimated by the equations in Table 3 is the gross total volume. In reality, much of this volume is empty space. The actual proportion of the volume occupied by branches and foliage is estimated by standing beneath the canopy or crown, beside the trunk, and obtaining a careful visual appreciation of the canopy structure. This proportion is then used to discount the air space in the crown volume: solid volume = V (m^3) × proportion of branches and foliage in crown volume.

TABLE 3 - Estimation of crown or canopy volume as a function of the shape of the crown

Approximate shape of the crown	Equation
Conical	$V(m^3) = \pi \times \frac{Db^2 \times Hc}{12}$
Parabolic	$V(m^3) = \pi \times \frac{Db^2 \times Hc}{8}$
Hemispherical	$V(m^3) = \frac{\pi \times Db^2}{12}$

Where possible, samples of branches and foliage should be taken to the laboratory in order to proceed with the determination of *WD* and dry matter in foliage. This ensures a more realistic approximation of biomass, leaving the estimation of foliage density as the only more subjective element in the estimation.

Literature pertaining to the calculation of *WD* of the crown is scarce. For the methodology presented here, a conservative approach is taken. Where the *WD* value of the tree is known, this value is divided in half to give an approximation of the density of leaves and small branches in the crown. Where the *WD* is unknown, then half the average for the *WD* values found for species in the quadrat plot or even in the same mapping unit or land cover polygon isapplied.

Calculation of total aboveground biomass

Total biomass is calculated for each tree in the sample quadrat by the addition of the trunk and crown biomass estimates, then summing the results for all trees in the sample quadrat. This value can then be converted to tonnes per hectare. To the tree biomass estimate in the 10 × 10 m quadrat, the estimates from shrubs, deadwood and debris measured in the nested 5 × 5 m quadrat need to be added. Shrub volume is estimated in a similar way to that of the trunk of trees, by calculating the volume of the stem. However, considerable reductions in wood density are applied given the much larger moisture content in the green tissue of shrubs. Moreover, the contribution to volume due to foliage in the case of shrubs is considered negligible. Therefore, it is not considered in the overall estimation of total biomass.

The herbaceous layer, the litter and other organic debris collected in the field from the 1 × 1 m quadrat are taken to the laboratory, dried and weighed. The resulting value is the dry organic matter estimate per square metre. The resulting biomass calculation is then extrapolated to the 100 m^2 of the largest quadrat. This last figure can then be added to the estimates of biomass of tree trunk and crown (canopy) calculated earlier. The resulting calculation should yield a value of total aboveground biomass for each of the field sampling sites (10 × 10 m quadrats).

Minimum data sets for aboveground biomass estimation

Given the importance of aboveground biomass for carbon accounting, and as these estimations are used to derive inputs into the modelling of dynamics of soil carbon (SOC), the certain minimum data sets should be gathered during field surveys.

Both the allometric and the regression equation estimation methods require the data in Table 4.

TABLE 4 - Minimum data set for aboveground biomass estimation

Variable / measurement	Unit
Tree height	m
Diameter at breast height	cm
Length of the crown	m
Width of the crown	m
Height to base of the crown	m
Proportion of branches and foliage in canopy volume	%

In addition, some specific information is required about the tree species in order to complete the data sets, namely:

- wood density,
- volumetric coefficient,
- some method to readily calculate the density of wood plus foliage of the canopy with minimal field data.

These variables are the minimum data set for biomass estimation. They are easily obtainable and can be measured at low cost.

Estimation of belowground biomass

In any biological system, C is present in several known forms in pools and compartments. In terrestrial systems, it is convenient to divide these reserves into aboveground and belowground pools. This section is concerned with the belowground biomass pool.

Estimation of root biomass

Roots play an important role in the carbon cycle as they transfer considerable amounts of C to the ground, where it may be stored for a relatively long period of time. The plant uses part of the C in the roots to increase the total tree biomass through photosynthesis, although C is also lost through the respiration, exudation and decomposition of the roots. Some roots can extend to great depths, but the greatest proportion of the total root mass is within the first 30 cm of the soil surface (Bohm, 1979; Jackson *et al.*, 1996). Carbon loss or accumulation in the ground is intense in the top layer of soil profiles (0-20 cm.). Sampling should concentrate on this section of the soil profile (Richter *et al.*, 1999).

Non-destructive (conservation) methods rely on calculations of belowground biomass for similar types of vegetation and coefficients as reported in the literature. They are derived from the measurement of the aboveground biomass.

Santantonio, Hermann and Overton (1977) suggest that the biomass is close to 20percent of the total aboveground biomass and indicate that the majority of the underground biomass of the forest is contained in the heavy roots - generally defined as those exceeding 2mm in diameter. However, it is recognized that most of the annual plant growth is dependent on fine or thin roots. The data available and recorded in the literature are limited, owing to the high costs involved in the collection and measurement of root biomass. According to MacDicken (1997), the ratio of belowground to aboveground biomass in forests is about 0.2, depending on species. A conservative estimate of root biomass in forests would not exceed 10-15percent of the aboveground biomass. A reasonable estimate from the literature is: belowground biomass = aboveground forest biomass × 0.2.

TABLE 5 - Non-destructive methods for root biomass estimation

METHOD	EQUATION	APPLICABILITY
Winrock (MacDicken, 1997; Bohm, 1979)	Species × 5:1	Trees
	More loss than outlined in literature	Shrubs
Santantonio, Hermann and Overton (1997)	**BGB = Volume AGB × 0.2**	Trees
	BGB = Belowground biomass	Shrubs
	AGB = Aboveground biomass	
Kittredge (1944) Satoo (1955)	log $W = a + b$ log DBH	Trees
	W = dry weight of tree component (roots)	Shrubs
	DBH = Diameter breast height (1.3 m)	
	a and b are regression coefficients	
Ogawa *et al*. (1965)	log $W = a + b$ log d^2h	Trees
	W = dry weight of tree component	Shrubs
	d = DBH	
	h = height of tree	
	a and b are regression coefficients	
Unattributed	log $W = a + b$ log $(d^2 + h + d^2h)$	Trees
	W = dry weight of tree component	Shrubs
	h = height of tree	
	d = DBH	
	a and b are regression coefficients	

Where a satisfactory estimate of volume and DBH of the aboveground component of plants is available, this information can be used to derive an estimate of the belowground biomass. The accuracy of the estimates depend noticeably on the size and selection of the sample, as suggested by Kittredge (1944) and Satoo (1955), who proposed the use of allometric regression equations of the weight of a given tree component on DBH, such as those of the form:

$$\log W = a + b \log \text{DBH}$$

where W represents the weight of a certain component of tree, DBH is the diameter at breast height (1.3 m), and a and b are regression coefficients. Although this type of regression has proved useful in several types of forests (Ovington and Madgwick, 1959; Nomoto, 1964; Ogino, Sabhasri and Shidei, 1964), a more exact estimation can be made using DBH^2h, where h is the height of the tree (Ogawa *et al.*, 1965). Nevertheless, Bunce (1968) showed that the inclusion of height improved the estimation of dry weight of the tree component marginally. In some cases, another expression was preferred: $DBH^2 + h + DBH^2h$. The knowledge of the weight of the trunk can generally increase the accuracy of the estimation by virtue of its correlation with root weight (Ogawa *et al*., 1965). As for correlation with the weight of branches and leaves, the regression is consistent. However, it would vary with species and even between families of a single species. Age and density of stems has shown inconsistent associations with roots (Satoo, 1955).

The growth of roots in length can be considered similar to that of the branches using the radial increase of these when it is visible, although the thickness of the roots can change with age. Table 5 provides a summary of non-destructive methods.

Several methods exist to measure roots directly. These are essentially destructive methods that are used for measurements required in ecological and agronomic research. They are:

- excavation,
- auger cores,
- monolith method.

The Winrock International Institute of Agriculture (MacDicken, 1997) reports that the auger core sampling and the monolith methods of measurement of roots are economically more feasible than excavation. Therefore, these two methods are described briefly.

The sampling in these methods must be done when the biomass in the roots is at its highest, but avoiding the growing season. A correction factor of 1.25-2.0 can be applied to the mass of roots after the data have been collected. This factor is based on considerations of the losses due to sampling and processing.

The sampling of soil cores to determine the root biomass is usually carried out at a standard soil thickness of 0-30 cm. In contrast, monolith sampling is used to determine the relative distribution of roots below a depth of 30 cm. The choice of method depends on specific site conditions and includes considerations on: the accuracy required; the availability of data about the expected distribution of roots in the soil for the species inventoried; soil depth; soil texture; and stoniness.

The soil auger core method uses a cylindrical tube 15 cm in length and 7-10 cm in diameter, with an extension of about 1 m. It removes or displaces a known volume of soil from a soil profile of known depth. A core of 50-80 mm in diameter is considered sufficient. The auger corer can be inserted manually or mechanically. Manual insertion of the auger corer is not practical for depths greater than 50 cm or for clayey or stony soils. In sandy dry soils, a small diameter core may be necessary in order to reduce soil losses while extracting the core. In very stony soils, and particularly where these have many woody roots, coring may not be possible. In these circumstances, it may be more practical to take a known volume of soil through a monolith taken from the face of a cut or cross section of soil corresponding to a cut, trench, hole or naturally occurring gully in the landscape.

Ideally, the sample of the profile should be to the limit of the depth of the root system. Rooting intensity changes with soil depth, but the spatial variability of root intensity is typically high. However, the limits of the sample can be based on initial observations of the walls of the soil profile. In some cases, the sample can be based on an exponential model that relates root distribution to the mass of the main stem of the root. This function could be used to extrapolate root density in the soil samples. As far as possible, soils must be sampled to a minimum depth of 30 cm.

The best manner to examine roots is to wash them immediately after extraction from the cores. The core samples can be stored in polyethylene bags in a refrigerator for a few days or in a freezer until examination and processing. Dry weight must be verified by weighing of dry biomass or by loss-on-ignition methods. The texture, the structure, degree of compaction and the organic matter content have great influence on the precision and time required to extract the roots from the cores. The extraction involves a sieve or strainer of 0.3-0.5 mm mesh. The work can be simplified by a superficial washing and by combining strainers with 1.1 and 0.3 mm mesh. The first strainer will contain most roots, the second will contain the rest. The material taken from the strainers can also be mixed with water and the suspended material poured off (live roots of most species have a specific gravity near to 1.0). The remainder can be classified manually in a container under water (to remove fragments of organic matter and dead roots).

The fine roots are a small but important part of the system for the assimilation of water and nutrients. This functional distinction helps in classifying the root systems according to size. The class limits need to fall between 1 and 2 mm of root diameter. Roots larger than 10 mm in diameter are not sampled by the soil core. For herbaceous perennial vegetation, roots can be separated into classes of greater than and less than 2 mm. In mixed vegetation, the separation of roots of different species is difficult. Sampling in homogenous soils may not capture the spatial variability of root density, which is claimed to have weight variation coefficients commonly in excess of 40 percent. In heterogeneous soils, the variation coefficient can be much higher. This variability implies that many samples are required in order to estimate the weight of roots and the belowground biomass component. It is advisable to obtain experimental information from one or two sites on the nature of spatial variation of both soils and root distribution, where available.

The monolith method requires cutting a monolith of the soil, from which the roots are separated by washing. This method is frequently used for quantitative determinations of roots. Small monoliths can be sampled with simple tools such as a shovel. However, the use of machinery is required for the excavation of a trench front to be sampled.

The size of the monolith varies depending on the species of plant being investigated. Generally, the volume of a monolith varies between 1 and 50 dm3. The samples of the monolith can be obtained with a board of stainless steel pins nailed in wood. The size of the pinboard is determined by the type of pins, based on previous observations of depth and distribution of rooting. The soil collected with the pinboard is heavy (a sample of a block of 100 cm × 50 cm × 10 cm of soil can weigh almost 100 kg.). The soil is washed away, exposing the roots for observation. If rough soil fragments are shown in the mesh before putting the board in the ground, it will be of help to maintain the roots in the original location while the sample is washed. The washing of the sample can be facilitated through cold water soaking for clayey soils and soaking in oxalic acid for calcareous soils. Washed root samples can be stored in polyethylene bags for a short time in a refrigerator, but preferably they should be stored in a freezer. The samples are dried for 5 hours to 105 °C in an oven. The results can be expressed in dry matter per unit of volume of soil.

Choosing a belowground biomass estimation method

The methods presented thus far vary in their degree of rigour. There is an obvious trade-off between rigour and accuracy and cost and practical viability. In summary, it is felt that destructive sampling is not a feasible option owing to its high costs in terms of money, resources, effort and time. The data available from measurements obtained from any of the destructive methods that are reported in the literature are limited. This is so, again, because of the high cost of root sampling and measurement.

In summary, non-destructive methods should be preferred, particularly in situations where there may be an empirical function relating stem diameter or any other allometric measurement to root biomass. It is recommended that in situations where no empirical equation exists, the root volume and biomass should be estimated as a fraction of the aboveground biomass, as an interim measure, in order to estimate total biomass. Later, if time, circumstances and budget allow, the assessor should aim at developing regression equations of root biomass as a function of easy or cheap-to-measure variables, such as DBH or simply diameter of the stem at the base of the trunk. Obtaining the data to develop such regression functions will require samples obtained by some of the destructive methods described above.

In the case studies described in this report, the following relationships were used to estimate belowground biomass:

- for coniferous vegetation: belowground biomass = 0.25 aboveground biomass,
- for broadleaf vegetation: belowground biomass = 0.30 aboveground biomass.

Mapping biomass in present land use

A single method for the quantification of biomass with universal application has not yet been developed or identified. This report presents three methods for biomass estimation, with differing requirements and results.

The spatial representation of variations in biomass across the study area can be achieved by first computing the total biomass (i.e. aboveground and belowground) for each quadrat site.

Mapping total biomass

The sum of the aboveground and belowground biomass, as calculated with the procedures described above, is total biomass of the vegetation in the actual land use sampled by the quadrat site. This is calculated for each quadrat sampling site (10 × 10 m) and is expressed in tonnes per hectare.

Each quadrat sampling site lies within a given polygon that represents a land cover or land-use class, which was mapped by multispectral satellite image classification or air-photo interpretation or digitized from an existing paper map. The areas within each polygon (vector) or class (raster) are representative of homogenous vegetative cover types. The quadrat sites are also georeferenced from the GPS readings on the ground. The sampling design assured that all polygons received at least one quadrat site to represent them. For land cover polygons containing more than one quadrat site, total biomass for each polygon can be estimated by the following procedures.

Upscaling of biomass estimates from polygon or class averages

This procedure involves the calculation of the following:

- average of total biomass estimates for all quadrat sites within the polygon;
- upscaling by converting the total biomass averaged over the quadrat sites and their area to the total area covered by the polygon.

Procedures based on within-class averages carry the implicit assumption that the area of the polygon is sufficiently homogenous in vegetative cover to allow reliable spatial interpolation of data within the polygon boundaries. Issues of within-polygon spatial variability of total biomass may be a concern, particularly in situations of large differences between quadrat site biomass estimates within a given polygon.

MAPPING CARBON STOCK IN PRESENT LAND USE

Two main carbon pools are identifiable in a landscape:

- C in biomass,
- C in soils.

The first pool is the carbon stock in vegetation including living biomass and dead vegetation. The latter is the C present in SOM in its different forms and compartments, including litter in different degrees of decomposition. The remainder of this section focuses on simulation modelling and estimation procedures of SOM turnover in soils and carbon accumulation in the different SOC pools in present land use.

CARBON STOCK AS BIOMASS

The calculation of carbon stock as biomass consists of multiplying the total biomass by a conversion factor that represents the average carbon content in biomass. It is not practically possible to separate the different biomass components in order to account for variations in carbon content as a function of the biomass component. Therefore, the coefficient of 0.55 for the conversion biomass to C, offered by Winrock (1997), is generalized here to conversions from biomass to carbon stock: C = 0.55 × biomass (total). This coefficient is widely used internationally, thus it may be applied on a project basis. The results may be displayed in a similar fashion to totalbiomass.

Total carbon in present land use

The estimation of total C in present land use should include the carbon stock as biomass and the SOC present in the SOM. This estimation would consist of converting the SOM value reported for the soil mapping units in the study area to SOC. The content of SOC included in SOM may change depending of the type of organic residues present in the SOM. In turn, this changes with management and other factors. However, determining the composition of residues in SOM and the spatial variability of the different qualities of SOM in the soil is a difficult task. For estimation purposes, a generic coefficient can be assumed in order to transform SOM to SOC: SOC = 0.57 SOM.

Multiplying the values of SOM by this coefficient and then transforming them from percentage values to tonnes per hectare can be done through computing a weighted average of SOM over the layers of the analysed soil profiles that represent each soil mapping unit. The weights correspond to the thickness of each horizon multiplied by its soil bulk density.

Where required, spatial interpolation and other procedures for upscaling estimates would help in mapping SOC for the entire area of concern. Adding these SOC values to the C present as biomass would yield the total carbon stock for the present land use, as follows: carbon stock $_{(total)}$ = C as biomass + SOC.

In interpreting results from carbon stock calculations, the rather dynamic nature of SOM should be borne in mind. The relatively fast turnover of SOM, particularly in agricultural lands and other managed soils, implies that a value of carbon stock calculated from SOC values derived from SOM can only be reliable for a relatively short period of time. The relatively large contribution of soils to total CO_2 emissions to the atmosphere (about 30 percent for agricultural soils) points to the need for a dynamic simulation of the turnover of SOM, with the consequent partition of C in the various pools within the soil. Land management has significant effects on the interannual and intra-annual variations in SOM and can make the difference in terms of the soil being an emitter or a sink. Thus, the need for dynamic simulation modelling of SOM turnover is linked strongly to the issue of stock permanence.

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Biomass, net primary production and impact of bamboo plantation on soil redevelopment in a dry tropical region

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Abstract

Growth and impact of a bamboo (*Dendrocalamus strictus* (Roxb.) Nees) plantation on mine spoil in a dry tropical region were examined. Culm dynamics, biomass, net primary production, soil microbial biomass and N-mineralization were estimated at ages 3, 4, and 5 years. The recruitment of culm population varied between 18% and 36% and shoot mortality from 6–7% per year. Net accumulation of green culms during 3rd and 4th year was 3999 and between 4th and 5th year 10854 ha^{-1}. Total biomass was 46.9 t ha^{-1} in the 3-year old to 74.7 t ha^{-1} in the 5-year old plantation with 35% occurring belowground. Total net primary production (NPP) ranged between 20.7 t ha^{-1} (3-year old) and 32.0 t ha^{-1} (5-year old), of which aboveground net production was 17.0 to 24.7 t ha^{-1} (between 3 to 4, and 4 to 5 years, respectively). Accounting for only 14% of the total biomass, foliage contributed 36% to NPP. Nutrient deposition through leaf litter was 45–79 kg N and 6–11 kg P ha^{-1}. Litter bag experiment indicated 235 days for 50% and more than 1000 days for 95% decomposition. Amounts of N and P deposition and release increased with the age of the plantation. Rate of N-mineralization increased from 3.3 (3 years) to 6.9 $\mu g\ g^{1}$ $month^{-1}$ (5 years). The proportion of mineralized-N converted into nitrate decreased with age. Soil microbial C increased from 127–319, microbial-N from 19–38 and microbial-P from 9–16 $\mu g\ g^{-1}$ soil between 3 to 5 years. With increasing age of plantation, a greater proportion of soil C, N and P tended to be immobilized in soil microbial biomass. Net primary production and the soil redevelopment process exhibited a positive feed-back relationship.

Keywords: *Dendrocalamus strictus*; Litter decomposition; Microbial biomass; Mine spoil; Net primary production; N-mineralization; Restoration; Soil redevelopment

1. Introduction

Opencast coal mining removes surface earth, piling it over unmined land to form chains of external dumps. Mine spoils are physically, nutritionally and biologically impoverished habitats, therefore their natural recovery is a slow process (Wali and Pemble, 1982; Wali, 1987; Jha and Singh, 1991, 1992). Restoration of such habitats requires the establishment of a self-sustaining soil/plant system. Artificial restructuring of vegetation is often essential to check the soil erosion, to restore the soil fertility and to accelerate the natural recovery process (Singh and Jha, 1993;

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Dobson et al., 1997). Vegetation contributes to the accumulation of soil organic matter and plant nutrients. Development of a sufficient organic matter pool to serve as an N source and sufficient N-mineralization potential resulting into nutrient release rates that are adequate for plant growth are essential for sustaining vegetation at an acceptable level of production (Bradshaw et al., 1986). Microorganisms contribute to the re-establishment of biogeochemical processes, and play an important role in soil redevelopment and in the maintenance of soil fertility.

The influence of plant species on the soil, redeveloping under plantations on mine spoils could vary from species to species. For example, Alexander, 1989a, b compared the effects of *Acacia albida* and *Eucalyptus camaldulensis* on the tin-mine spoil in Jos Plateau, Nigeria, and found that *A. albida* was able to improve both the nutrient status and physical conditions in the top 20 cm of the soil beneath its canopy, whereas *E. camaldulensis* caused a progressive increase in the soil acidity and reduction of base content. We believe that a desirable species for planting on mine spoils should posses the ability to (i) grow on poor and dry soils, (ii) develop the vegetation cover in a short time and to accumulate biomass rapidly, and (iii) improve the soil organic matter status and microbial biomass, thereby enhancing the supply of plant-available nutrients. In addition, the species should be of multipurpose economic use.

The bamboo *Dendrocalamus strictus*, a perennial woody tropical grass, is a constituent of native dry tropical forests (Tomar, 1963; Singh and Singh, 1991a). It is a quick-growing and hardy species occurring on a wide range of soil conditions with particularly luxuriant growth on porous, coarse-grained dry soils with low moisture retaining capacity and on well-drained, sandy loam soils overlying boulders on hill sides with an optimum pH 5.5–7.6 (Yadav, 1963). On account of extensive shallow root system and accumulation of leaf mulch, bamboo serves as an efficient agent in preventing soil erosion and conserving moisture, and its plantations are effective for the control of soil erosion, stream bank protection, reinforcement of embankments and drainage channels, etc. (Yadav, 1963). Additionally, bamboo is an important commercial source for a variety of purposes, such as manufacture of paper, construction of houses, bridges, furniture, bags and baskets, and is also utilized, although to a limited extent, as fuel and fodder. The felling cycle varies between 3–5 years.

In this study we assess the impact of *D. strictus* on soil conditions during the early phases of mine spoil restoration. Since mine spoils are characterized by the loss of soil both in the pedological and biological senses, this study provided an opportunity to understand the soil redevelopment processes following a massive ecosystem degradation. We also compare the biomass and net production levels of *D. strictus* attained in plantation on mine spoil with those of native dry tropical forest. Restoring drastically disturbed ecosystems to acceptable levels of production could contribute to counteracting emissions of CO_2 to the atmosphere.

2. Materials and methods

2.1. Study site

The experimental plots were located at the Jayant project in the Singrauli coalfield which extends over 2200 km^2 (lat. 23°47′–24°12′N, long. 81°48′ to 82°52′ E, and elevation 280–519 m above msl). The climate is tropical monsoonal and the year is divisible into a mild winter (November–February), a hot summer (April–June) and a warm rainy season (July–September). A meteorological station established on the site showed that the mean monthly minimum temperature within the annual cycle ranges from 6.4–28°C and mean monthly maximum from 20–42°C. The annual rainfall averages 1069 mm, of which about 90% occurs during the period from late June to September. The rainfall is characterized by a high degree of interannual variation, for example during the 1980–1994 period it ranged from 673 to 1450 mm $year^{-1}$. The bulk density of the soil was 1.67 g cm^{-3}, water holding capacity 25.50%, pH 7.03, and soil texture sandy (78.43% sand, 9.13% clay and 12.43% silt). The potential natural vegetation of the area is a dry tropical deciduous forest, in composition similar to that described by Singh and Singh (1991a).

2.2. Stocking density and plant biomass

Plantation of *Dendrocalamus strictus* was raised in July–August 1991 on fresh mine spoil by planting

8-month old nursery-raised seedlings in previously dug pits (40 cm × 40 cm × 40 cm) at a spacing of 2 m × 2 m. Three plots, each 15 m × 15 m in size, were established in 1994. Number of bamboo clumps per plot varied from 45–47. Five clumps in each plot were marked and the number of culms in each clump was counted annually from 1994 (3-year old) to 1996 (5-year old). Bamboo shoots were categorized into current year, old, and standing dead shoots. All culms were measured 10 cm above the ground for circumference and tallied into five size classes between 5 and 15 cm at 2 cm intervals. Fifteen culms of different size classes were harvested. The oven-dry weights of different components, viz. stem, foliage, rhizome, and root were determined. Least squares regression equations were developed to estimate dry weights of each component from culm diameter (Table 1). Biomass for each component for each size class was multiplied by the number of culms in that size class. Summation of values across size classes yielded total biomass, which was calculated separately for each plot for each year.

2.3. Net productivity

Net primary production (NPP) was calculated for the 1994–1995 (4-year old), and 1995–1996 (5-year old) growth cycles separately for each of the three plots, from foliage and current stem biomass and net biomass accumulation in different components using the following expression:

$$\mathrm{NPPn} = \mathrm{FBn} + \mathrm{CSBn} + \Delta\mathrm{OSB} + \Delta\mathrm{DSB} + \Delta\mathrm{RhB} + \Delta\mathrm{RB} + \mathrm{NLLn}$$

where, NPPn = net primary production of *n*th year, FBn = foliage biomass in *n*th year, CSBn = stem biomass of current shoots in *n*th year, (OSB = change in old stem biomass between $n-1$ and *n*th year, (DSB = change in dead shoot biomass between $n-1$ and *n*th year, (RhB = change in rhizome biomass between $n-1$ and *n*th year, (RB = change in root biomass between $n-1$ and *n*th year, and NLLn = non-leaf litter deposited in *n*th year.

2.4. Leaf litter decomposition

For assessing the dry matter loss through decomposition, freshly fallen leaves were collected during May–June 1994. Nylon net litter bags (10 cm×10 cm, 1 mm mesh), containing 5 g of air-dried leaf litter were placed on the floor of bamboo plantation in the month of June 1994. Dry weight of the air-dry litter was determined on samples from the same stock. Three litter bags were recovered from each plot at each of the six sampling dates. The recovered litter was air-dried, adhering soil particles were carefully brushed off, and then oven dried at 80°C to constant weight.

The mean relative decomposition rate (MRD) was calculated by using the formula

$$\mathrm{MRD}\,(\mathrm{mg\,g^{-1}\,day^{-1}}) = \ln(W_1 - W_0)/(t_1 - t_0)$$

where W_0 is the weight of litter at time t_0, W_1 the weight of litter at time t_1, and $t_1 - t_0$ is the sampling interval (days). The daily instantaneous decay rate (k) of litter for the study period was calculated using the negative exponential decay model of Olson (1963): $W_t/W_0 = e^{-kt}$, where W_0 is the initial weight and W_t the weight remaining after time t. The time required

Table 1
Constants (a), slopes (b), coefficients of determination (r^2) for regression equations relating biomass to culm diameter. Values in parentheses are 1 SE

Components	*a*	*b*	r^2	P
Stem [a]	4.7 (0.2)	1.7 (0.2)	0.93	<0.001
Foliage [b]	4.1 (0.2)	0.5 (0.1)	0.87	<0.001
Rhizome [c]	−155.0 (70.6)	182.1 (19.7)	0.91	<0.001
Root [a]	3.6 (0.3)	1.6 (0.2)	0.83	<0.001

[a] Ln $Y = a + b$ Ln X.
[b] $Y = \exp(a + bX)$.
[c] $Y = a + bX$.

for 50% and 95% weight loss was calculated as $t_{50} = 0.693/k$, and $t_{95} = 3/k$, respectively.

2.5. Soil sampling and analysis

Three soil samples were collected at random from each of the three permanent plots using $15 \times 15 \times 10$ cm monoliths during September in 1994, 1995 and 1996. The samples from within a plot were thoroughly mixed to yield one composite sample per plot. Large pieces of plant materials were removed and the field-moist soil was sieved through a 2 mm mesh screen. Each soil sample was divided into two parts. One part in the field-moist condition was used for the measurement of available nutrients (NH_4-N, NO_3-N and PO_4-P), and for the determination of microbial C, N and P. The other part was used for the determination of dry weight, total organic C, kjeldahl N and total P.

Organic C was determined by dichromate oxidation and titration with ferrous ammonium sulphate (Moore and Chapman, 1986). Kjeldahl N was determined by the microkjeldahl method (Jackson, 1958), and NH_4-N was extracted by 2 M KCl and analysed by the phenate method (APHA, 1985). NO_3-N was measured by the phenol disulphonic acid method, using $CaSO_4$ as the extractant (Jackson, 1958). Biocarbonate extractable Pi was determined by the ammonium molybdate-stannous chloride method (Sparling et al., 1985). The soil was digested in a triple acid mixture of $HClO_4$, HNO_3, and H_2SO_4 (1 : 5 : 1) and the digest was analysed for P by a phosphomolybdic acid blue colour method (Jackson, 1958).

2.6. Microbial biomass

The field-moist soil was preincubated by spreading it overnight in a thin layer between two sheets of polyethylene, with the moisture content adjusted to 40% water holding capacity, then transferred to polyethylene bags and incubated for 7 days at 25°C in a large air-tight container that held two vials, one containing 20 ml distilled water to maintain 100% relative humidity and the other containing sodalime to absorb CO_2. The container was aerated every day by opening the lid for a few minutes. After 1 week, the soil was taken out, mixed and analysed for soil microbial biomass C, N and P by fumigation extraction method (Brookes et al., 1982, 1985; Vance et al., 1987). In brief, preconditioned soil samples (50 g) were saturated with purified liquid $CHCl_3$ for 10–20 h (Srivastava and Singh, 1988). The $CHCl_3$ was subsequently removed by evacuation and then the soil was extracted with 0.5 M K_2SO_4 (1 : 4, soil : extractant) for 30 min for the biomass C and N estimates. For biomass P, another soil sample was extracted with 0.5 M $NaHCO_3$ for 30 min. Extracts of unfumigated preconditioned soil samples were also obtained.

Microbial C was determined in the mine spoil extracts of fumigated and unfumigated samples by dichromate digestion following Vance et al. (1987). Biomass C (MBC) was then estimated by the equation, $MBC = 2.64\ E_C$, where E_C is the difference between C extracted from the fumigated and non-fumigated soils (Vance et al., 1987). On the same K_2SO_4 soil extracts, biomass N was determined as total N using the kjeldahl digestion procedure. The flush of total N (K_2SO_4-extractable N in unfumigated soil subtracted from that of fumigated soil) was divided by a KN (fraction of biomass N extracted after $CHCl_3$ fumigation) value of 0.54 (Brookes et al., 1985). Biomass P was determined as inorganic P in the $NaHCO_3$ extracts of fumigated and unfumigated soils by the ammonium molybdate-stannous chloride method (Sparling et al., 1985). Biomass P was calculated by dividing the flush of inorganic P ($NaHCO_3$-inorganic P in fumigated soil minus that in the unfumigated soil) by a KP value of 0.40 assuming that 40% of P in the soil microbial biomass is released as inorganic P by $CHCl_3$ (Brookes et al., 1982). All results are expressed on an oven dry soil (105°C, 24 h) basis.

2.7. N-mineralization

N-mineralization was measured by the buried bag technique (Eno, 1960). Two fresh, field-moist, sieved (2 mm) soil samples (150–200 g each) were sealed in large polyethylene bags and buried in soils at 15 cm depth in each plot. Coarse roots and large fragments of organic debris were removed in order to avoid any marked immobilization during incubation. Nitrate-N and ammonium-N were analysed (as mentioned above) at time zero and after 30 days of field incubation. The increase in the concentrations of ammonium and nitrate-N over the course of field incubation is defined as net N mineralization and the increase in

nitrate-N only as nitrification. All results are expressed on an oven-dry soil (105°C, 24 h) basis.

2.8. Statistical analysis

The data were subjected to multifactor Analysis of Variance, and regression analysis using the Statgraphics package (Statistical Graphics Corporation, 1986). Differences in means were tested using multiple range tests.

3. Results

3.1. Culm dynamics, biomass and net primary production

Distribution of live and dead culms in different size classes, for 3rd, 4th and 5th year is summarized in Table 2. The majority of green culms were in the 9–13 cm circumference class, while the dead culms, which averaged 30% of the total culms, dominated the 5–7 cm class. Of the total culms, 14–15% were represented by current year shoots and 54–55% by old shoots. The recruitment to culm population was 5864 ha^{-1} between the 3rd and 4th year, and 13 679 ha^{-1} between the 4th and 5th year. Corresponding values for mortality were 1863 culms ha^{-1} and 2824 culms ha^{-1}; this resulted in net accumulation of 3999 green culms between the 3rd and 4th year and 10 854 green culms ha^{-1} between the 4th and 5th year.

Total biomass increased from 46.9 t ha^{-1} in the 3-year old to 74.7 t ha^{-1} in the 5-year old plantation (Table 3). ANOVA indicated significant differences due to age in the biomass of foliage, old stem, rhizome, root and total biomass. For all the above components only the 5th year biomass was significantly different from that of the previous years (Table 3).

The contribution of different components of the plant to total stand biomass was remarkably consistent across the three ages. A majority of biomass was contributed by live stems ($\overline{x} = 42.2\%$) followed by rhizomes ($\overline{x} = 25.3\%$). Foliage accounted for 14% of the total biomass while roots contributed 9.4%. Thus 65.3% biomass was located above the ground and 34.7% below-ground.

There was a marked temporal variation in the distribution of biomass in the stems of different size classes (Fig. 1). In the stems of current shoots, a majority of biomass resided in the 11–13 cm size class in the 3-year and 4-year old plantation (62.2% and 55.8% respectively), while this size class in the 5th year accounted for only 23.7%. The 11–13 cm size class also harboured a majority of biomass in the old

Table 2
Distribution of green and dead culms in different size classes of *D. strictus* plantation on coal mine spoil

	No. of culms ha^{-1} ± 1 SE					Total
	Circumference class (cm)					
	5–7	7–9	9–11	11–13	13–15	
3-year old						
Green	2145 ± 515	3242 ± 2033	10540 ± 773	5502 ± 1958	1046 ± 597	22475 ± 3754
Dead	6500 ± 938	2682 ± 1120	713 ± 645	0	0	9895 ± 764
Total	8645 ± 1210	5923 ± 940	11253 ± 1958	5502 ± 1958	1046 ± 597	32368 ± 3232
4-year old						
Green	2714 ± 390	5027 ± 1714	10117 ± 890	7137 ± 1335	1478 ± 561	26474 ± 2164
Dead	7990 ± 795	2835 ± 1052	933 ± 742	0	0	11758 ± 955
Total	10704 ± 1161	7862 ± 808	11051 ± 1517	7137 ± 1335	1478 ± 661	38232 ± 1651
5-year old						
Green	4998 ± 504	9758 ± 767	10657 ± 1051	8808 ± 699	3108 ± 471	37328 ± 264
Dead	9886 ± 597	3229 ± 990	1467 ± 933	0	0	14582 ± 1323
Total	14884 ± 857	12988 ± 718	12123 ± 1681	8808 ± 699	3108 ± 471	51911 ± 1063

Table 3
Oven-dry stand biomass of bamboo plantation at different ages on mine spoil

Components	Biomass (t ha^{-1} ± 1 SE)		
	3-year old [a]	4-year old [a]	5-year old [a]
Foliage	6.1a ± 1.2	7.9a ± 0.6	10.7b ± 0.3
Current shoot stem	4.5a ± 0.6	3.7a ± 0.6	5.4a ± 0.3
Old shoot stem	15.3a ± 3.0	19.6a ± 1.6	26.4b ± 0.9
Dead shoot stem	4.5a ± 0.8	5.3a ± 0.9	6.7a ± 1.2
Rhizome	11.9a ± 1.6	14.0a ± 1.0	18.8b ± 0.7
Root	3.6a ± 0.4	4.1a ± 0.2	5.3b ± 0.1
Total	46.9a ± 6.8	55.8a ± 4.1	74.7b ± 2.4

[a]Values in a row suffixed with different letters are significantly different from each other at $P<0.05$.

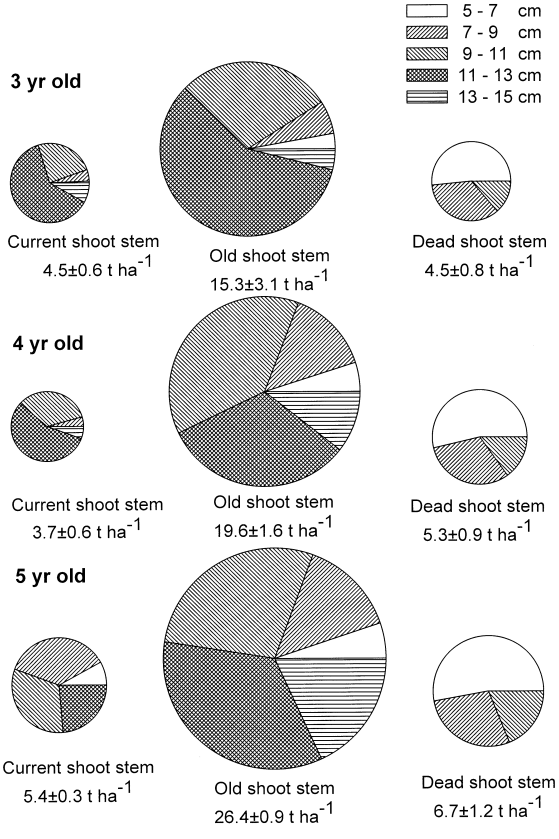

Fig. 1. Distribution of biomass in different size classes of current, old and dead stems of the bamboo plantation at ages 3, 4 and 5 years. Values below the pies are total biomass ± 1 SE.

shoots in the 3rd year (58.4%) but contribution of this size class was reduced when the plantation became older (32.3–34.4%). This temporal fluctuation reflected the different recruitment rates of stems into different size classes. Most of the biomass (>50%) in the dead shoot was accounted by the size class 5–7 cm. Within the stem component, greatest accumulation of biomass occurred in stems of old shoots (Fig. 1).

Net primary production could be calculated only for the 4th and 5th year (Fig. 2). The total net primary production (NPP) of the 5-year old plantation was one and one-half times greater than that for the 4-year old plantation. Net production of each component (foliage, current stem, old stem, dead stem, rhizome and root) was higher for the 5th year compared to the 4th year, but the differences between the 2 years were statistically significant only for foliage, and root. For both the years, stem contributed maximally (42.2%) to NPP followed by foliage (36.1%), rhizome (12.3%) and root (7.9%). The current stems accounted for 40–42%, old stems 48–50%, and dead stems 9–10% of stem production. While the contribution of roots to NPP was remarkably constant (about 7.9%), that of foliage and rhizomes showed mild fluctuation. Thus in comparison to 38.6% and 9.8% contribution, respectively by foliage and rhizomes in the 4-year old plantation, these components accounted for, respectively, 33.7% and 14.7% of NPP in the 5-year old plantation.

3.2. Litter decomposition and nutrient return

The litter bag experiment indicated a significant inverse exponential relationship between per cent weight remaining (Y) and time (X) according to $Y = 100\ e^{-0.0032X}$ ($R^2 = 0.9716$, $P<0.001$) (Fig. 3). Decomposition parameters indicated that for 95%

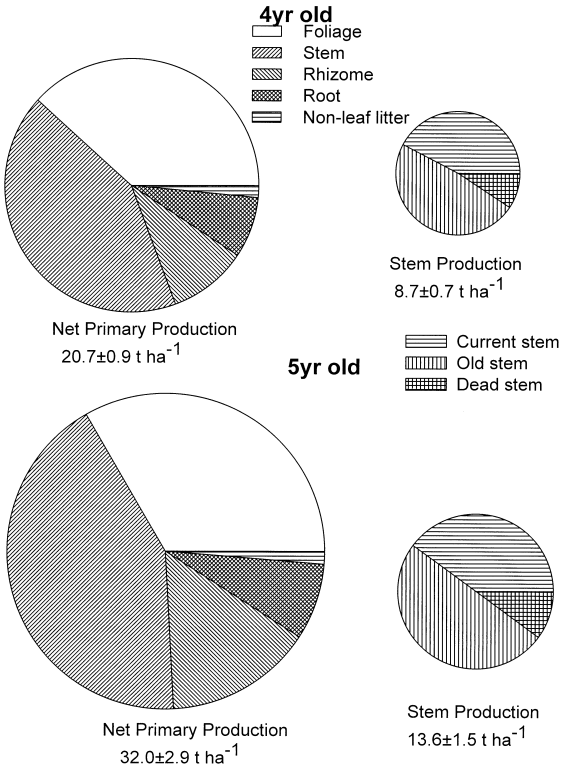

Fig. 2. Share of different plant components in total NPP of bamboo plantation. Values below the pies are total net production ± 1 SE. The pies on the right represent distribution of stem net production in current, old and dead categories.

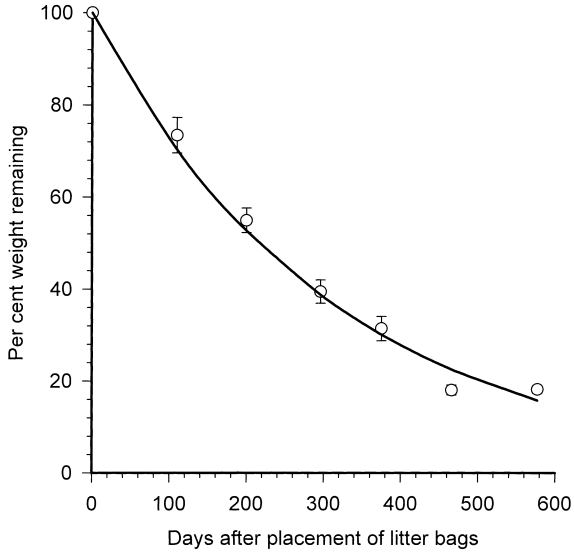

Fig. 3. Relationship between per cent weight of leaf litter remaining and time elapsed since placement of litter bags on plantation floor. Bars are 1 SE and the fitted line represents the regression equation.

Table 4
Decomposition parameters for bamboo leaf litter

	(mean ± 1 SE)
Decay constant (year^{-1})	−1.08 ± 0.03
Mean relative decomposition rate (mg g^{-1} day^{-1})	2.28 ± 0.018
Time for 50% decomposition (days)	235 ± 6
Time for 95% decomposition (days)	1016 ± 27

mass loss about 2.8 years will be needed, while 50% decomposition occurred within about 8 months (Table 4). The fresh litter of bamboo contained 0.74% N and 0.103% P. Since this bamboo is deciduous, annual leaf fall is equivalent to foliage biomass. On the basis of foliage biomass (Table 3), N and P contents, and mean relative decomposition rate (Table 4), N and P cycling is calculated in Table 5, which shows increasing amounts of deposition and release of N and P with the age of the plantation.

3.3. Soil microbial biomass and nutrient availability

Soil C, N and P contents are given in Table 6. Organic C and kjeldahl N increased with age. ANOVA indicated significant differences in organic carbon and

Table 5
Deposition of N and P through leaf fall and release through decomposition

Age (year)	Leaf fall (kg ha^{-1} year^{-1})	N deposition (kg ha^{-1} year^{-1})	P deposition (kg ha^{-1} year^{-1})	N release (kg ha^{-1} year^{-1})	P release (kg ha^{-1} year^{-1})
3	6150	45.51	6.33	37.89	5.27
4	7900	58.46	8.14	48.68	6.78
5	10680	79.03	11.00	65.81	9.16

Table 6
Carbon and nutrient contents of soil and microbial biomass

Parameters	Plantation age (mean ± 1 SE)		
	3-year [a]	4-year [a]	5-year [a]
Soil organic C (%)	0.34a ± 0.02	0.50b ± 0.01	0.67c ± 0.01
Soil kjeldahl N (%)	0.04a ± 0.00	0.05b ± 0.00	0.07c ± 0.00
Soil total P (%)	0.01a ± 0.00	0.01a ± 0.00	0.01a ± 0.00
SOC : KN	8.48a ± 0.28	9.22ab ± 0.56	10.05b ± 0.13
NH_4-N ($\mu g\ g^{-1}$)	3.2a ± 0.2	3.4a ± 0.2	3.7a ± 0.1
NO_3-N ($\mu g\ g^{-1}$)	0.9a ± 0.1	1.1a ± 0.1	1.2a ± 0.2
Mineral N ($\mu g\ g^{-1}$)	4.1a ± 1.7	4.5a ± 0.3	4.9a ± 0.1
PO_4-P ($\mu g\ g^{-1}$)	8.0a ± 0.6	8.0a ± 0.6	8.8a ± 0.4
Microbial biomass C ($\mu g\ g^{-1}$)	126.8a ± 14.2	217.6b ± 9.8	319.1c ± 10.6
Microbial biomass N ($\mu g\ g^{-1}$)	19.2a ± 3.0	29.3b ± 2.4	37.5c ± 2.9
Microbial biomass P ($\mu g\ g^{-1}$)	9.1a ± 0.2	12.7b ± 0.1	16.2c ± 0.2
SOC in biomass C (%)	3.77a ± 0.55	4.38ab ± 0.28	4.74b ± 0.13
TN in biomass N (%)	4.82a ± 0.86	5.38a ± 0.19	5.61a ± 0.47
Total P in biomass P (%)	7.46a ± 1.14	9.45ab ± 1.26	12.13b ± 2.04
MB-C/MB-N	6.72a ± 0.32	7.47a ± 0.30	8.56b ± 0.39
MB-C/MB-P	13.93a ± 1.27	17.10b ± 0.82	19.73c ± 0.42
N concentration of microbial biomass (%)	7.48a ± 0.36	6.71b ± 0.28	5.86c ± 0.26
P concentration in microbial biomass (%)	3.65a ± 0.35	2.93a ± 0.14	2.53b ± 0.05

[a]Values in a row suffixed with different letters are significantly different from each other at $P<0.05$. SOC = soil organic carbon, KN = kjeldahl nitrogen, MB-C = microbial carbon, MB-N = microbial nitrogen, MB-P = microbial phosphorus.

Table 7
Nitrogen mineralization in soils under bamboo plantation

Age (year)	Nitrification ($\mu g\ g^{-1}\ month^{-1}$)	N-mineralization ($\mu g\ g^{-1}\ month^{-1}$)
3	1.2a ± 0.2	3.3a ± 0.4
4	1.7b ± 0.1	5.2b ± 0.0
5	1.9c ± 0.2	6.9c ± 0.2

Values in a column suffixed with different letters are significantly different from each other at $P<0.05$.

kjeldahl N due to plantation age. Total P however, did not differ significantly with age of the plantation.

Although mineral P and mineral N contents also increased with age, the increases were not statistically significant. On the other hand, N-mineralization rate increased significantly with the age of the plantation (Table 7). Interestingly, the proportion of mineralized-N converted to nitrate-N decreased with age. NO_3-N was 35.1% of mineralized-N in 3-year old plantation while it was 32.1% and 27.4% at ages 4 and 5 years, respectively.

Microbial C, N and P contents increased significantly with age (Table 6). Proportions of soil organic C, total soil N and total soil P reflected in microbial biomass increased, while the concentrations of N and P in biomass calculated by assuming that dry biomass contains 50% carbon decreased with the age of the plantations (Table 6). There was a concomitant increase in biomass C : N and C : P ratios (Table 6).

4. Discussion

4.1. Culm recruitment and mortality

In *D. strictus* culms emerge during the rainy season from nodes located on the rhizomes of the previous year culms and grow to full height before branching in about 3–4 months. The production of new culms is linearly related with the number of old culms in a clump, and the majority of new culms is produced by the rhizomes of 1–2 year old culms (Tomar, 1963). Taylor and Zisheng (1987) reported average annual recruitment of culms between 8.2% (*Fargesia spathesia*) and 13.7% (*Fargesia scabrida*) in bamboos which form the dominant understorey under montane and subalpine forests of Sichuan, China, and Tripathi and

Singh (1996) found 10.6–12.3% recruitment in a mature *D. strictus* plantation in the Indian dry tropics. The annual recruitment in the present plantation on mine spoil varied from 18 (between the 3rd and 4th year) to 36% (between 4th and 5th year). Among the three species of *Fargesia*, the annual mortality varied between 8.5% and 10.6% (Taylor and Zisheng, 1987), and in a mature *D. strictus* plantation it was 6.6–10.6% (Tripathi and Singh, 1996). These mortality rates are comparable to the rates observed for the present *D. strictus* plantation on mine spoil (6–7%). Thus the mine spoil habitat proved favourable to growth and survival of *D. strictus*.

4.2. Biomass and net primary production

The quantity of biomass per unit area constitutes the primary inventory data needed to understand the flow of nutrients and water through the ecosystem. The bamboo plantation developed on the mine spoil accumulated a substantial amount of biomass. Compared to 30–49 t ha^{-1} in the present study, several bamboo forests and plantations recorded 0.8 to 24 t ha^{-1} aboveground biomass (Veblen et al., 1980; Taylor and Zisheng, 1987; Rao and Ramakrishnan, 1989; Tripathi and Singh, 1996). The aboveground biomass recorded for *Sasa kurilensis* in Japan (90 t ha^{-1}, Oshima, 1961), *Chusquea culeou* in San Pablo, Andes (158.8 t ha^{-1}, Veblen et al., 1980) and *Arundinaria alpina* in Kenya (100 t ha^{-1}, Wimbush, 1945). In the native dry tropical deciduous forest, aboveground biomass ranged between 42–78 t ha^{-1} (Singh and Singh, 1991a). In the native dry tropical forest, 86% of the tree biomass was allocated aboveground and 14% belowground, compared to 65% and 35% in the present *D. strictus* plantation. In the present plantation, foliage accounted for as much as 14% of the total biomass compared to 7% in the native dry tropical forest (Singh and Singh, 1993), which should contribute to a high level of primary productivity.

Comparison with data on biomass from tree plantations on mine spoils also indicated superiority of *D. strictus*. A 3-year old black locust plantation on mine spoils in Kentucky yielded 5.8 to 18.5 t ha^{-1} aboveground biomass (Creighton et al., 1983). Ten-year old plantations of eastern-cotton wood, virginia pine and black locust accumulated between 36 and 45.4 t ha^{-1} aboveground biomass (Vail and Wittwer, 1982).

Net primary production in *D. strictus* plantation ranged between 20.7 (3-year old) and 32.0 t ha^{-1} (5-year old) compared to 11.3–19.2 t ha^{-1} $year^{-1}$ of the native dry tropical forest (Singh and Singh, 1991a). Aboveground net primary production in bamboo forests and bamboo plantations ranged between 1.5–11.0 t ha^{-1} $year^{-1}$ (Veblen et al., 1980; Taylor and Zisheng, 1987; Tripathi and Singh, 1996) compared to 17.0–24.7 t ha^{-1} $year^{-1}$ in the present study. Isagi et al. (1993) have reported 24.6 t ha^{-1} $year^{-1}$ aboveground net primary production for *Phyllostachys bambusoides* in Japan. In this study, of the total NPP, foliage accounted for 33.7–38.9%, and of the aboveground net primary production, 43.3–46.5%. In the native dry tropical forest, tree and shrub foliage contributed 30% of NPP (Singh and Singh, 1993) and 38–57% of the aboveground tree net production (Singh and Singh, 1991a). Thus in this plantation foliage accounted for a significant proportion of ecosystem function as is also true for the native dry tropical forest. Production efficiency (i.e., NPP per unit weight of leaf) ranged between 2.6 to 3.0 and compared with 3.3 reported for a variety of deciduous species in south-eastern USA (Hedman and Binkley, 1988).

The high NPP and relatively smaller biomass resulted into short mean residence time (biomass accumulation ratio, biomass : net production) of various plant compartments. The biomass accumulation ratio averaged 1 year for foliage, 5 years for culm, 5 years for rhizome and 2.3 years for roots. Isagi (1994) recorded biomass accumulation ratio of 6 years for culms of *Phyllostachys bambusoides* and this ratio for the dry tropical forest trees averaged 13.7 (Singh and Singh, 1991a). The biomass accumulation ratio of bamboo culms is in consonance with 3–5 years felling cycle. However, since most of the products of bamboo stem are long lasting, the accumulated C would remain sequestered for a long time.

4.3. Litter deposition, decomposition and nutrient release

Fast turnover (1 years) of the foliage compartment and its large share of NPP cause a substantial amount of nutrients to be deposited on the floor by the bamboo plantation each year. The present values of nutrient deposition (45–79 N and 6–11 kg P) compare with the range 51.6–69.6 N and 3.1–4.3 kg P ha^{-1} $year^{-1}$

reported for native dry tropical forest (Singh and Singh, 1991b), and 40.8 N and 3.5 kg P ha^{-1} $year^{-1}$ for a mature *D. strictus* plantation on unmined Ultisol (Tripathi and Singh, 1995).

The release of deposited nutrients depends on the rate of decomposition. Roy and Singh (1994) reported a decay constant between 1.93 and 2.26 for dry deciduous forest litter, and Tripathi and Singh (1992) recorded a decay constant of 1.51 for leaf litter of bamboo planted in natural dry tropical habitat. Thus while *D. strictus* leaf litter takes 235 days for 50% decomposition and more than 1000 days for 95% decomposition on mine spoil, the corresponding values for natural unmined habitat are 168 and 725 days. Leaf litter of natural forest on the other hand, takes only 113–133 days for 50% decomposition, and 488–576 days for 95% decomposition. The relatively slow decomposition of bamboo leaf litter should lead to soil organic matter build up in the long run and is expected to provide benefits of mulching. Because of the accumulation of leaf mulch bamboo serves as an efficient agent in preventing soil erosion and conserving soil moisture (Yadav, 1963).

4.4. Impact of plantation on soil redevelopment

The high inputs of litterfall in the *D. strictus* plantation were reflected in increasing contents of soil organic C and kjeldahl N with the age of the plantation. The soil under 5-year old plantation had 98% greater C, and 67% greater N compared to that under 3-year old plantation. The recorded widening of soil C : N ratio (from 8 to 10) is an indication of vegetation effect. In contrast to soil organic C and kjeldahl N, there was no significant difference with age in mineral N or PO_4-P. On the other hand, the rate of N-mineralization increased significantly with age. The N-mineralization under 5-year old plantation was twice as much as that in the 3-year old plantation. Evidently the increasing demand by the aggrading plant biomass does not permit the mineral N and P to accumulate. Studies on the native forest ecosystems yielded a rainy season range of 2.1–6.8 μg mineral N μg g^{-1} and 1.2–3.1 μg PO_4-P g^{-1} dry soil, and N-mineralization rates of 18–48 μg N g^{-1} $month^{-1}$ (Roy and Singh, 1994, 1995; Jha et al., 1996). Thus while the mineral N pool in the bamboo plantation was comparable, even in the 5-year old plantation, the N-mineralization rate was only 14–40% of that in the native forest. This indicates the high nutrient use efficiency of the bamboo. In both the native forest and the bamboo plantation, the dominant form of available N was ammonium, which could indicate a preferential uptake of nitrate by plants (Jha et al., 1996). Nevertheless, in the bamboo plantation, although absolute net rate of nitrification increased with NH_4 availability (N-mineralization), only 35 (3-year old)–27% (5-year old) of mineralized N was converted into NO_3-N by nitrifying bacteria. The greater abundance of ammonium could be at least partly due to less efficient nitrification process, or due to substantial microbial assimilation of NO_3 as argued by Stark and Hart (1997). The increasing abundance of less mobile form of plant-available N is a precursor of progressively tighter nutrient cycle.

Substantial amounts of C, N and P were immobilized in microbial biomass, and the magnitude of immobilization increased with age in conformity with increasing soil organic C and kjeldahl N. The microbial biomass levels recorded in this study are still much lower than in native forest ecosystems but are comparable to those observed in naturally vegetating mine spoils (Srivastava et al., 1989). Studies have indicated positive relationships between microbial C and total soil C, and between microbial N and total soil N (Wardle, 1992; Ruess and Seagle, 1994; Singh and Singh, 1995). Addition of C and N simultaneously, as it happens through litter fall, should increase microbial biomass substantially by satisfying both the C and N limited components. In the present study while microbial C in the 5-year old plantation was 152% greater, microbial N and P were only 96 and 78% greater than in the 3-year old plantation. With the increasing age of plantation, greater proportions of organic C, kjeldahl N and total soil P tended to be immobilized in the microbial biomass indicating the soil redevelopment process. The ratio of microbial C to total soil C is reported to be a reliable soil microbiological index for evaluating the status of a restored ecosystem (Insam and Domsch, 1988). Stark and Hart (1997) have argued that, in ecosystems where soil C and N are accumulating, the microbial biomass will be a net sink for inorganic N, including NO_3.

The biomass C : N and C : P ratios increased with time and the N and P concentrations of microbial biomass decreased. These observations indicate a

possible change in the composition of microbial biomass. As the litter layer builds up, the food web in the soil may progressively become fungus dominated (Hendrix et al., 1986). An increase in the fungal component of microbial biomass during grassland restoration has been reported (Bentham et al., 1992). Fungi and bacteria have considerably different C : nutrient ratios. For example, the C : N ratio of fungal hyphae is higher (10–12) compared to that of bacteria (usually between 3–5) (Jenkinson and Ladd, 1981). Compared with higher turnover and C losses of bacterial population, fungal domination would lead to greater retention of microbial-C (Coleman and Hendrix, 1988; Singh and Singh, 1995). This is consistent with the increasing availability of NH_4 (i.e. N-mineralization), which is a preferred N-source for microbial communities (Recous et al., 1990). Increasing availability of N has been reported to increase immobilization of C in biomass (Elliott et al., 1983).

In this study the proportional increase in microbial biomass was substantially greater than the proportional increase in soil C or N, which is in conformity with Powlson et al. (1987) and Saffigna et al. (1989). Positive relationships have been reported between microbial biomass and soil structure, aggregate size and stability (Drury et al., 1991; Singh and Singh, 1995). Therefore, a rapid development of microbial biomass in the mine spoil is an indication of the efficient restoration potential of *D. strictus* plantation.

5. Conclusions

Dendrocalamus strictus planted on mine spoil attained similar biomass but higher net production levels compared to that of native dry forest within a short time. Accounting for only 14% biomass, foliage contributed 36% ecosystem function resulting into heavy deposition of organic matter on the soil surface. About one-third of plant biomass was located belowground. As much as 56% of NPP was directed to support the soil redevelopment process, and 44% was sequestered in perennial aerial structure which can be harvested and put to long-term use. These features augmented the soil microbiological processes which resulted in progressively greater proportions of soil C and nutrients being immobilized in microbial biomass, and a widening of soil C : N and biomass C : N ratios. Increasing availability of organic matter also enhanced N-mineralization and hence the supply of plant-available nutrients. Increasing abundance of less-mobile forms of plant-available N (i.e. NH_4-N) indicated a progressive tightening of nutrient cycling. During these early years of ecosystem redevelopment, the net primary production and soil processes indicated a positive feedback relationship.

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