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Journal:

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The usage of "et al." in long author lists will also be accepted:

Smith J, Jones M Jr, Houghton L et al. 1999. Future of health insurance. N Engl J Med 965: 325-329. DOI: 10.10007/s002149800025.

Book:

Rai MK, Carpinella C. 2006. Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam.

Chapter in the book:

Webb CO, Cannon CH, Davies SJ. 2008. Ecological organization, biogeography, and the phylogenetic structure of rainforest tree communities. In: Carson W, Schnitzer S (eds.). Tropical Forest Community Ecology. Wiley-Blackwell, New York.

Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

Information from the internet:

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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Effectiveness of co-management in reducing forest dependency and improving socioeconomics of forest dependent people in Bangladesh

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Abstract. *Yeasmin S, Islam KN, Jashimuddin M, Rahman MM, Jiku AC. 2022. Effectiveness of co-management in reducing forest dependency and improving socioeconomics of forest dependent people in Bangladesh. Asian J For 6: 56-64.* Co-management of forest protected areas (PA) has started its journey in Bangladesh, intending to conserve forest resources by creating alternative income-generating activities for forest-dependent people. This study was designed to assess the effectiveness of co-management initiatives in improving socio-economic status and reducing peoples' forest dependency at Dudpukuria-Dhopachari Wildlife Sanctuary (DDWS), Bangladesh. A total of 142 respondents consisting of 71 co-management project-supported people (treatment) and 71 local people (control) with similar socio-economic conditions without any project support, were surveyed randomly through a semi-structured questionnaire. The Difference in Differences (DiD) method was applied to assess the effectiveness of this program. Results revealed that there was an insignificant difference between co-management participants and non-participants in the case of total income. Both parties also observed a similar trend for total forest resource extraction. However, the monthly income of co-management participants from secondary occupations increased by USD 16.46. In contrast, the monthly fuel wood extraction of the co-management participants was reduced, equivalent to USD 2.21. The studied socio-economic parameters were more or less similar for both parties. We conclude that the co-management interventions in DDWS resulted from insignificant differences in terms of socio-economic conditions and forest dependency of local forest-dependent communities.

Keywords: Co-management, the difference in differences, forest dependency, protected area, socioeconomics

INTRODUCTION

Forests and people are two interconnected and crucial terms in forest resources management. Globally, about 1.6 billion people depend directly or indirectly on forest resources for their livelihood (United Nations 2011). In addition, poor people living in the vicinity of forested areas have multiple dependencies on forest resources – food, water, land, medicine, energy, timber, etc. for their subsistence. Due to the excessive extraction of forest resources and anthropogenic disturbances, tropical forests in developing and underdeveloped countries are being degraded and deforested daily. An estimated 420 million ha of forests have been lost worldwide through deforestation since 1990. During 2015-2020, the annual rate of deforestation was estimated at 10 million ha, seen from 12 million ha in 2010-2015 (FAO 2020).

Bangladesh, a developing country in South Asia, is facing various difficulties regarding forest resource conservation and management. Forested areas of the country are geographically distributed in the remote and underdeveloped parts of the country. People living in the vicinity of these government-owned forests are poor and ultra-poor. They encroach on forest land to make settlements and practice agriculture. In addition, they collect fuel wood, pole, timber, and other non-wood forest products from forests to meet their daily needs (Mukul et al., 2016; Ullah et al., 2020). Such detrimental activities accelerate forest degradation and deforestation in the country (Islam et al. 2019a; Abdullah et al. 2019; Ahmed et al. 2020). The Government of Bangladesh has taken some initiatives to conserve the reserve forests – rich in diverse native endangered flora and fauna. Some intact and less disturbed forest patches supporting rich biodiversity were declared protected areas (PA) as a part of conservation initiatives amid rapid forest cover loss (Feeroz 2013).

However, such a declaration was not fruited due to a lack of departmental capacity, peoples' socio-economic status, and immense dependence on forest resources (Mollah et al. 2004; Roy and DeCosse 2006). Later on, forest-dependent people were involved in the management body in the name of PA co-management. Forest resources co-management was initiated in Bangladesh with direct supervision and financial support from United States Aid for International Development (USAID) in 2004. The main objective of such intervention was to conserve biodiversity and to halt or reduce forest cover loss along with livelihood improvement of forest-dependent people through Alternative Income Generating Activities (AIGAs) (Rahman et al. 2017a). USAID supported this community-based management approach in three phases in the name of three different projects. Initially, the Nishorgo Support Project (NSP) during 2004-2008, then the Integrated Protected Area Co-management (IPAC) project during

2008-2013, and Climate Resilient Ecosystem and Livelihood (CREL) project supported co-management activities during 2013-2018 (Islam et al. 2019a). Presently, there are 54 forest PAs in the country, out of which 21 PAs are under a co-management regime with 28 co-management organizations (BFD 2022).

Researchers and policymakers are trying to investigate the outcomes of such community-based approaches to forest resources management from different angles across the globe. In Nepal, community-managed forests successfully increased forest cover and biodiversity conservation (Thoms 2008; Anup et al. 2018; Shrestha et al. 2018). Siraj et al. (2018) found community-based forest management successful in addressing deforestation and livelihood improvement of forest-dependent people in Ethiopia. However, In Malawi, forest co-management creates no discriminable impact on forest-based household income (Mazunda and Shively 2015). In addition, the misuse of power by important actors for self-interest has been considered a major obstacle to the success of community-based forest management (Krott et al., 2014). Magessa et al. (2020) concluded that the participatory forest management policy failed to achieve governance objectives and meaningful devolution in Tanzania.

In Bangladesh, researchers are also trying to assess this people-oriented governance system in terms of biodiversity conservation, reducing deforestation, and upliftment of the socio-economic status of forest-dependent people. Islam et al. (2019a) revealed that forest cover loss was in progress in co-managed PAs in Cox's Bazar and Sylhet region. However, Chowdhury et al. (2020) found positive impacts of co-management on forest cover in the Chattogram region. Livelihood programs under the umbrella of co-management in Chunati Wildlife Sanctuary (CWS) contributed to the increasing income of forest-dependent people and reduced forest dependency (Rahman et al. 2017a,b). Jashimuddin et al. (2021) outlined some positive impressions of co-management in CWS regarding governance and biodiversity conservation. Rahman et al. (2016) reported that biodiversity indices had dropped in some PAs during the co-management regime. In addition, some exotic species become dominant in co-managed PAs (Nath et al. 2016; Rahman et al. 2017b; Islam et al. 2020). Islam et al. (2020) concluded that non-co-managed forests showed better biodiversity status and carbon sequestration capacity than co-managed PAs. In line with this finding, Islam et al. (2021) revealed that forest officials and co-management non-participants perceived poor co-management outcomes concerning the existence of native tree species, wildlife population, and agricultural activities inside the PAs of Bangladesh.

Dudpukuria-Dhopachori Wildlife Sanctuary (DDWS) has been one of the co-managed PAs since 2011 in the south-eastern hilly Bangladesh region. Some studies are on the socio-economic impacts of co-management in different PAs of Bangladesh. But how this management approach has impacted the income and social lifestyle of forest-dependent people in the vicinity of DDWS has not been investigated yet. This study thus has been designed to (i) investigate the impact of co-management on the income of forest-dependent people, (ii) examine the changes in the forest resource extraction of forest-dependent people, and (iii) compare the social status of co-management participants and non-participants based on present livelihood practices.

MATERIALS AND METHODS

Study area

Dudpukuria-Dhopachori Wildlife Sanctuary (DDWS) was declared a wildlife sanctuary on 9 May 2010 under the Bangladesh Wildlife Act 1974, later amended and renamed as Wildlife (Conservation and Security) Act 2012. It is situated at the junction of Rangunia and Chandanish Upazila (sub-district) of the Chattogram District and lies between 22º09' N to 22º22' N and 92º05' E to 92º10' E (Figure 1). The sanctuary is under the jurisdiction of Chattogram South Forest Division. With a total area of 4716.57 ha, DDWS comprises three beats under two ranges, namely Dudpukuria, Kamalachori fall under Khurushia Range, and Dhopachari beat under Dohazari Range. The beat is the lowest administrative unit of the Bangladesh Forest Department (BFD). Ecologically, DDWS is a part of Bangladesh's evergreen and semi-evergreen tropical forests. The monthly average temperature ranges from 11.4ºC to 33.7ºC, the monthly average rainfall is 252.7 mm, and the monthly average humidity is 76.6% (BBS 2022). Most of the sanctuary is covered by hills and hillocks (80%), and only 20% is plain land (Hossain et al., 2013; NN, 2018).

About 5,000 people live across the Dudpukuria landscape portion, and another 12,000 people live across the Dhopachari landscape (NN 2018). People are engaged in multiple income sources to earn their total livelihood. They cultivate rice, vegetables, and fruits; some work as day laborers and some run small businesses. The poor and ultra-poor people depend on forest resources for their daily needs. Therefore, they encroached on forest lands to grow agricultural products and extracted trees, fuel wood, bamboo, saplings, etc. (NN 2018).

Sampling framework

A bottom-up approach is followed for governing the co-managed PAs. Administrative activities of co-management are centered at Forest Range Office; each range has all governance components led by the Co-management Executive Committee (CMEC), previously known as the Co-management Committee (CMC). At the bottom of the co-management governance, there are several Village Conservation Forums (VCF) consisting of forest-dependent people living in the villages in the vicinity of the PA. Co-management intervention in DDWS was enacted in 2011 by institutionalizing two CMCs, One in Khurushia Range and another in Dohazari Range, by USAID-funded IPAC and CREL projects. A sum of 36 VCFs were formed under two CMCs to facilitate co-management governance in DDWS. Out of 36 VCFs, 21 were under the jurisdiction of the Khurushia Range, while 15 were under Dohazari Range. VCF beneficiaries were aided with different AIGA

supports, e.g., fruits and medicinal plants, seedlings, vegetable seeds, fish, poultry, handicraft assistance, etc., throughout the project duration. We randomly selected eight VCFs – four from each range. A total of 71 VCF members from these eight VCFs were randomly selected as treatment respondents for the questionnaire survey.

We employed the Difference in Differences (DiD) method to estimate the net change in the respondents' income and forest resource uses due to co-management intervention. A DiD estimation is a well-known econometric tool for investigating causal relationships of a certain intervention; when implemented does not have equal impacts on everybody at the same time in a similar way (Bertrand et al. 2004; Lechner 2011). Hence, it needs data from two parties, one involved in the intervention named as treatment, and the other not involved named as the control. So, we interviewed another 71 people having no involvement with co-management intervention, which made the total sample size 142 (71 treatment, 71 control). However, we collected secondary information from the BFD and CODEC field staff (Community Development Center; a national NGO – associate partner of the co-management implementing body in DDWS). The survey questionnaire of the study focused on income sources, monthly income amount, forest resource uses, and monthly income from forest resource extraction both before and after initiation of co-management, as well as common socio-economic attributes like existing household appliances, energy, and drinking water sources, domestic waste management, sanitary latrine uses, etc.

Calculation of change in income status and forest resource extraction

As DiD method requires pre- and post-treatment information from control and treatment groups, we used a recall method for both groups to evoke them stating the pre-and post-treatment information on their livelihoods and forest resource uses. We classified income sources into two categories. Income sources that contributed a major share in respondents' livelihoods were termed primary occupations, and other supporting money-generating activities were listed as secondary occupations. Forest dependency was assessed by asking about the number of monthly visits to the forest, types, and quantity of resources collected and calculating the price per market value.

The attributes used in the DiD method, and their definitions, are explained in Table 1. We employed the following regression framework to assess the impact of co-management on a participant household by eliminating the time-varying impact on the group that was not caused by this intervention.

Let, the state of the household k under study be H_k , and the period during which the intervention occurs be P_t. Here, H_k= 1 if k is a participant of the livelihood support program and 0 (zero) if k is a non-participant or a controlled household. And again, if k = 1, then similarly, P_t= 1 at the end of the intervention period and 0 (zero) before the intervention.

Let $Y_{k,t}$ be the response variable of the household k at the end of the intervention program.

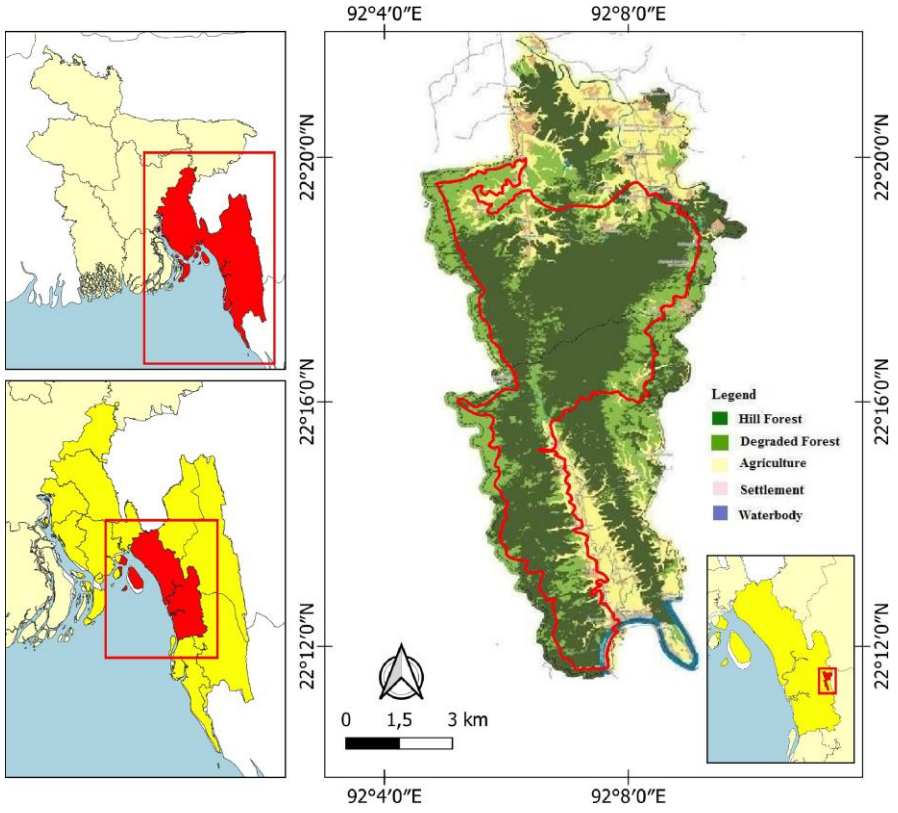

Figure 1. The landscape of Dudpukuria-Dophachari Wildlife Sanctuary, Bangladesh (Source: Winrock International)

Table 1. Derivations of the attributes of DiD method

Type of household	Period of measurement	Response variable
Treatment household	Pre-treatment[a]	$Y_{k,0}$
Control household	Pre-treatment	$Y_{c,0}$
Treatment household	Post-treatment[b]	$Y_{k,t}$
Control household	Post-treatment	$Y_{c,1}$
Difference in treatment household	Pre-treatment and post-treatment	$D_k = Y_{k,1} - Y_{k,0}$
Difference in control household	Pre-treatment and post-treatment	$D_c = Y_{c,1} - Y_{c,0}$
DiD between treatment and control household	Pre-treatment and post-treatment	$(Y_{k,1} - Y_{k,0}) - (Y_{c,1} - Y_{c,0})$

Note: [a]In 2011, as recalled by the respondents during the survey in 2017. [b]In 2017, during the survey

Thus, the regression takes the form of (1):

$$Y_{k,t} = \beta_0 + \beta_1 . H_k + \beta_2 . P_t + \beta_3 . (H_k * P_t) + e \quad (1)$$

Where ($H_k * P_t$) is the interaction term of intervention and period, β_0, β_1, β_2, and β_3 are the parameters to be estimated, and e is the normally distributed error term with mean zero and constant variance. Now, using equation (1), we get equations (2) through (5):

When *k* is a control household and *t* is before the intervention.

$$Y_{c,0} = \beta_0 \quad (2)$$

When *k* is a treatment household and *t* is before the intervention:

$$Y_{k,0} = \beta_0 + \beta_1 \quad (3)$$

When *k* is a control household and *t* is after the intervention:

$$Y_{c,1} = \beta_0 + \beta_2 \quad (4)$$

When *k* is a treatment household and *t* is after the intervention:

$$Y_{k,t} = \beta_0 + \beta_1 + \beta_2 + \beta_3 \quad (5)$$

Thus, the difference in difference in $Y_{k,t}$, or household *k* in an income-generating activity *i* can be measured by (6).

$$DiD = (Y_{k,1} - Y_{k,0}) - (Y_{c,1} - Y_{c,0}) = \beta_3 \quad (6)$$

Comparison of social status

Social status depends on different indicators. In our study, we focused on demographic information, information on property ownerships like land ownerships and types of households along other socio-economic parameters. Education is an important indicator of social status or social change. Therefore, information was collected on respondents' educational backgrounds and the presence of school-going children in respondents' households. We categorized the educational background of respondents into two classes; (a) primary level means if respondents at least have attended a primary school which ranged from class one to class five; (b) secondary level ranges education from class six to class ten. In addition, respondents were asked questions on other parameters like existing household appliances, sources of energy, sources of drinking water, cooking systems, etc. To highlight the difference in minimum hygiene and cleanliness practices between the two groups, we also collected information about the uses of sanitary latrines and ways of domestic waste management.

RESULTS AND DISCUSSION

Demographic attributes and income sources

Basic demographic attributes of treatment and control groups didn't show any significant differences. The mean family size ranged from 5.75 with SD ± 2.6 for treatment and 5.29 with SD ± 2.15 for the control group (Table 2). In addition, most of the people from both treatment (84.5%) and control (81.7%) groups had only primary level education, and a few respondents (treatment 15.5%, control 18.3%) had secondary level education. There were no significant differences in the presence of school-going children (Table 2). Most families from the treatment (86%) and control (83%) groups were found to send their children to school. Meanwhile, about three-quarters (74.65%) of the treatment group and 59.16% of the control group lived on encroached land, some of which managed to take the land as a lease or rent from big landowners (Table 2). However, about 15% of the respondent from both groups have their own land. Household conditions of both groups were also found to be similar. Almost all the people from the treatment and control groups (95.78%) lived in a hut, and only a few (3.22%) could afford brick-built houses with corrugated iron sheets (Table 2).

The income sources of the study area were not widely varied. Agricultural activities were prominent income-generating sectors. However, the study found respondents engaged in multiple income-generating activities, which were classified into two categories. Earning sources producing a major share of the livelihood were categorized as primary occupations, whereas other supporting income sources aside from a primary occupation were secondary. The most observed primary occupation was rice cultivation

(76.06%), followed by day labor (10.56%) and small business (5.63%). The remaining 4.93% of primary earning sources included masonry, driving, rubber cultivation, lemon cultivation, remittance, etc. (Table 3). On the other hand, vegetable cultivation was the most observed secondary occupation (79.45%). People grew seasonal vegetables like hyacinth bean, string bean, gourd, pumpkin, cucumber, ladies' finger, bitter gourd, chili, potato, and coriander around their homestead around the year. Other observed secondary occupations were day labor (6.85%), small business (6.85%), driving, and other minor services (6.85%) (Table 3).

Changes in monthly income status

Table 4 reports the income status change between treatment and control groups before and after co-management intervention. It showed no significant changes in total income status due to the intervention between the group involved in the project and those who were not. There was no significant change in the income from primary sources too. However, the treatment group had increased their income (USD 16.46) from secondary occupations. The main secondary occupation of the respondents was vegetable cultivation.

Changes in monthly forest resource extraction

Table 5 shows the change in monthly forest resource extraction (USD) by treatment and control groups. Local people depended on different kinds of forest resources for their daily necessities. DDWS produces several forest resources like timber, pole, fuel wood, medicinal plant, bamboo, cane, broom, various wild fruits, etc. No significant change was found in the total amount of monthly forest resource extraction (Table 5). The main three resources-fuel, wood, bamboo, and saplings, were particularly analyzed to see the extraction changes due to co-management intervention. The monthly fuel wood extraction of the treatment group was reduced by USD 2.21 (Table 5). However, there was no significant change in monthly bamboo and sapling extraction.

Table 2. Demographic attributes of households surveyed

Variable	Treatment	Control
Family size (Mean number)	5.75 (± 2.6)	5.29 (± 2.15)
Educational status (% of respondents)	Primary level: 84.5 Secondary level: 15.5	Primary level: 81.7 Secondary level: 18.3
School-going children (% of households)	86	83
House types (% of households)	Hut: 95.78 Brick-built house: 3.22	Hut: 95.78 Brick-built house: 3.22
Land ownership (% of households)	Encroached: 74.65 Leased/rented: 8.45 Owned: 15.5	Encroached: 59.16 Leased/rented: 26.76 Owned: 14.08

Table 3. The occupation pattern of the respondents surveyed

Types of occupation	Percentage of respondents (%)			
Primary Occupation	Agricultural activities	Labor	Small business	Others
	78.88	10.56	5.63	4.93
Secondary Occupation	Vegetable cultivation	Labor	Small business	Others
	79.45	6.85	6.85	6.85

Table 4. Changes in the respondents' monthly income (USD*) in Dudpukuria-Dhopachari Wildlife Sanctuary, Bangladesh

Parameters	Total income	Income from primary occupations	Income from secondary occupations
$Y_{c,0}$	82.67	72.91	11.86
$Y_{k,0}$	122.61	103.76	15.73
$Y_{c,1}$	70.77	54.81	16.55
$Y_{k,1}$	122.47	85.56	36.88
D_c	11.9	-18.1	4.69
D_k	-0.14	-18.18	21.15
DiD	11.75 (1.01)	-0.08 (-0.01)	16.46 (2.47**)

Note: Values in parentheses are t-statistics, $D_c = Y_{c,1} - Y_{c,0}$; $D_k = Y_{k,1} - Y_{k,0}$; DiD = D_k - D_c; *USD = (1 USD = 82.98 BDT in 2017); **Significant at 5% level

Table 5. Change in value (USD per month) of extracted forest resources in Dudpukuria-Dhopachari Wildlife Sanctuary, Bangladesh

Parameters	Fuelwood	Bamboo	Sapling	Total
$Y_{c,0}$	5.38	3.93	2.85	12.23
$Y_{k,0}$	7.27	3.59	3.32	13.11
$Y_{c,1}$	4.64	3.01	2.83	10.55
$Y_{k,1}$	4.32	2.81	2.20	9.68
D_c	-0.74	-0.91	-0.02	-1.68
D_k	-2.95	-0.78	-1.12	-3.42
DiD	-2.21 (-1.90*)	0.14 (0.26)	-1.1 (-1.02)	-1.74 (-1.24)

Note: Values in parentheses are t-statistics. *Significant at 10% level

Table 6. AIGA supports provided by co-management intervention

Provided AIGA supports	Percentage (%)
Fruit and medicinal plant seedlings and vegetable seeds	61.97
Fruit and medicinal plant seedlings, vegetable seeds and fish	4.23
Fruit and medicinal plant seedlings and fish	2.82
Fruit and medicinal plant seedlings and handicrafts	2.82
Fruit seedlings and vegetable seeds	23.93
Only vegetable seeds	1.41
Only fish	1.41
Only handicrafts	1.41

Linking monthly income changes with co-management intervention

The co-management supported or treatment group of DDWS was aided by local fruit and medicinal plant seedlings such as *Mangifera indica* L., *Artocarpus heterophyllus* Lam., *Syzygium cumini* (L.) Skeels, *Litchi chinensis* Sonn., *Ocimum sanctum* L., *Phyllanthus emblica* L., etc., seasonal vegetable seeds, fish, poultry, and handicraft assistance. Table 6 represents the distribution pattern of AIGA supports provided to the co-management participants of DDWS. Participants were found to receive different combinations of more than one AIGA supporting item, whereas very few participants received only one item. Among the combinations, the maximum number of participants (61.97%) were supported with fruit and medicinal plant seedlings and vegetable seeds, followed by 23.93% of participants receiving fruit and medicinal plant seedlings. The remaining participants received different combinations of all other supports (Table 6). Among the AIGA supports, participants were found to generate money by cultivating and selling seasonal vegetables from the seeds provided. However, not all fruit and medicinal seedlings became suitable for harvesting within six years. Very few participants reported they could harvest some fruits. Fish farming and handicrafts assistance were found to be provided to a small extent that also could not generate any significant income.

Moreover, participants supported with poultry failed to produce any profit due to unknown poultry diseases and early death. Therefore, the study did not find any potential support to uplift the treatment group's total income over the control group. Hence, supported peoples' income status was seen partially improving when the income sources were categorized.

Comparison of socioeconomic condition

The present socio-economic condition of both the treatment and control groups was found to be almost similar. No significant differences were found among the studied attributes. All the parameters analyzed for both groups generated almost similar results. Figure 2 depicts the comparison of the presence of existing household appliances, energy sources, types of cooking systems, domestic waste management, and drinking water sources between the two groups. The treatment group was a bit ahead in owning television (treatment 18.3%, control 11.27%). The Control group was found to be in a better position in the case of energy sources. More people from the control group were using electricity, solar energy, and a mix of electricity and solar energy than the treatment group. People depending on kerosene and having no good source of energy were large in number from the treatment group (treatment 25.35%, control 18.3%). However, the percentages of people using the Improved Cooking System (ICS) were more in the treatment group than in the control group (treatment 16.9%, control 11.27%) (Figure 2). Lastly, the treatment group was also found to be in better condition in the case of sanitary latrine use; 93% of participants were found to use sanitary latrines, whereas the percentage of non-participants was 87.3%.

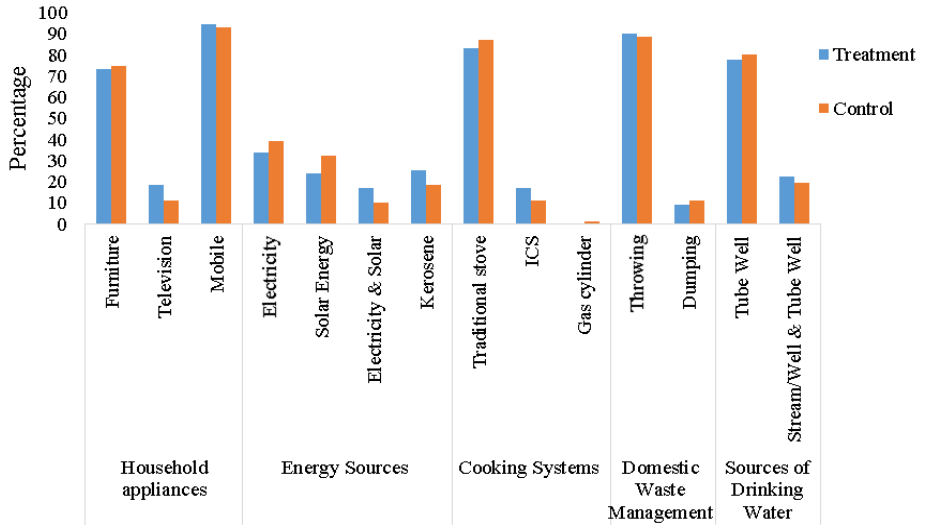

Figure 2. Comparison between treatment and control groups in terms of socio-economic parameters

Discussion

Changes in monthly income status

Co-management is a hard reality in some developing and underdeveloped countries in Asia and Africa (Islam et al., 2020). However, scientific findings regarding the outcomes of this community-based approach to forest resources management are not on the same line. This study unveiled that AIGAs support didn't significantly improve the income status of co-management supported groups. However, participants increased by USD 16.46 from their secondary occupation (Table 3). Participants could generate profit from seasonal vegetable cultivation among the AIGAs supported in the study area under a co-management scheme. There were also some individual stories of big success. One participant was found to make good profits from vegetable cultivation that surpassed income from his primary occupation. Several studies (Mukul and Quazi 2009; Sohel et al. 2009; Das 2013; Rahman et al. 2017a; Islam et al. 2019b) reported from different PAs of Bangladesh provided evidence that co-management brought positive changes to the income status of participants.

Changes in forest resource extraction

Though total forest resource extraction wasn't notably reduced, results found a reduction of USD 2.21 in monthly fuel wood extraction for the co-management participants group, which was a good sign of the change (Table 5). Similar to our study, Alam et al. (2014) found that the forest resource collection has decreased gradually in Teknaf Wildlife Sanctuary – an important co-managed forest PA of the country since 2004. Chen et al. (2012) stated positive improvement in family income and forest conservation through implementing community-based nature conservation initiatives in China. In addition, community-based conservation initiatives in Nepal contribute to livelihood improvement and forest resources conservation (Bijaya et al., 2016).

Socio-economic comparison

Estimates from demographic attributes were almost similar for both groups. The majority of both parties lived on encroached land and in low-cost-built houses and had poor educational backgrounds (Table 2). However, almost all the households from both treatment and control groups sent their children to school, which was a good indicator. Existing household appliances, sources of energy and drinking water, etc. parameters were examined to check participants' economic solvency. Types of the cooking systems were estimated assuming traditional stoves are more fuel wood oriented while ICS consume fewer fuels hence helping reduce fuel wood extraction. But the study did not find any sign that co-management provided or helped the participants regarding this issue. Some other NGOs, excluding studied co-management programs, were aided by some treatment and control owning ICS. Percentage uses of sanitary latrines and domestic waste management were measured to see if the intervention improved the hygiene status of the supported community. No studied parameters notably showed that co-management brought progressive changes in forest-dependent communities' lifestyles. In Ghana, a community-based conservation approach positively affected human capital but had minimal impact on the other capital, including household well-being and resilience (Akamani and Hall 2015). Using the Sustainable Livelihood Framework for a co-managed protected area in Madagascar, Ward et al. (2018) also found that co-management's perceived livelihood outcomes are negative and unevenly distributed.

Challenges

Several challenges might override the effectiveness of this intervention. One of the key factors could be people's livelihood dependence on agricultural practices. People of the study area mainly depend on traditional agricultural practices from the beginning of their settlement. Mukul et al. (2017) also reported that agricultural practices, illegal felling, encroachment, and removal of minor forest products are some of the major threats to co-managed PAs in Bangladesh. Phromma et al. (2019) indicated a similar issue for Phu Kao-Phu Phan Kham National Park, Thailand, that the protected area might control resource access to some extent but cannot resist agricultural expansion. Pulhin et al. (2007) and De Royer et al. (2018) also reported that co-management in the Philippines and Indonesia is still struggling due to the absence of social justice, unstable policy, bureaucratic procedures, weak institutional support, etc.

In conclusion, co-management intervention in DDWS brought partial as well as little changes in the income status and forest resource extraction behavior of forest-dependent people. Co-management-supported and non-supported peoples' lifestyles also showed no significant differences. Participants' livelihood experienced partial improvement mainly from vegetable cultivation though there were a few examples of other activities like planting fruit and medicinal plant species, fish farming, handicrafts, etc. In contrast, participants' forest resource extraction for fuel wood collection showed a small reduction.

This study specifies that provided supports were insufficient, and people became economically solvent enough to change and improve their lifestyle and gradually become less forest dependent. One reason could be that the provided AIGAs support did not create a wide range of non-forestry income variations. More non-forestry income-generating activities will increase participants' income resilience and free them from going to the forest, reducing forest disturbances significantly. The study suggests initiating more diversified non-forestry income-generating activities To increase households' income resilience. From field observation, the study suggests occupations like automated rickshaw pulling, CNG-run auto-rickshaw driving, running a small business, poultry rearing, handicraft making, etc., as some prospective options.

Another big challenge is continuity and success sustainability once any positive change starts occurring. Most of the time, these changes come from donor-funded projects. So, there is a big possibility of reverting to the previous state once the project ends. However, success stories could be continued if the governance of co-

management and the supported participants have a strong backup plan. Therefore, it is also necessary to prepare well-thought planning and guidelines for managing this sustainability after the project.

Limitations of the study

This study was conducted in only one co-managed protected area out of 21 in Bangladesh. Therefore, more precise results might be derived if the study considers a few more protected areas.

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Agroforestry potential of Kanchanpur District, Nepal using remote sensing and Geographic Information System

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Abstract. *Subedi PB, Mahara S, Paudel S , Bhandari J, Thagunna RS. 2023. Agroforestry potential of Kanchanpur District, Nepal using remote sensing and Geographic Information System. Asian J Agric 7: 65-74.* Researchers are interested in agroforestry because it can reduce poverty and land degradation, mitigate climate change, and improve food security. This study aimed to determine the land potential for agroforestry in Kanchanpur District, Nepal, using Geographic Information System modeling concepts and a variety of ancillary (soil fertility) and satellite data (Digital Elevation Model, wetness, Normalized Difference Vegetation Index, and Land Use Land Cover) sets. It was accomplished by logically integrating various thematic layers in the GIS domain. For Kanchanpur District of Nepal's Sudurpaschim Province, agroforestry suitability maps showed that 76.14 percent was very high suitable, 3.12 percent was highly suitable, 13.89 percent was medium, 5.67 percent was low suitable, and 1.15 percent was very low suitable. The use of remote sensing and GIS to find suitable land for agroforestry have significant impacts, which will significantly aid in the study of agroforestry practices and the estimation of crucial factors for optimal productivity. Such analyses and results will undoubtedly assist agroforestry policymakers, and planners put it into practice and expanding in new areas. GIS modeling has enormous potential for land resource mapping, eventually contributing to the benefit of poor rural people, especially farmers, and helping ensure food and environmental security and a sustainable livelihood.

Keywords: Agroforestry, ancillary data, GIS modeling, soil fertility, thematic layers

INTRODUCTION

The term "agroforestry" was coined in response to a surge in global interest in tree management and planting (Munsell et al., 2022). Agroforestry is a dynamic discipline of natural resource management that combine crops and trees on farmlands to sustain, diversify, and increase environmental, social, and economic benefits for user groups at all levels (Wanjira and Muriuki 2020). This definition encompasses both non-woody and woody agroforestry components and their ecological and economic aspects. Simply put, agroforestry links forestry and agriculture, ensuring the long-term use of land resources (Tiwari et al., 2017).

Trees play a more significant role in biodiversity conservation and environmental protection (Gustafsson et al., 2020). Domestication of trees on farmland not only improves soil fertility but also improves microclimate, acts as a windbreak, and serves as a fence; on a larger scale, trees aid in enhancing the region's hydrological cycles and increasing wildlife diversity (Raj et al., 2019). Similarly, agroforestry trees provide a diverse range of domestic goods in addition to food, medicine, and timber. Farmers have begun to consider trees as part of their livelihood rather than just a forest resource, providing fuelwood and other goods (Khadka et al., 2021). In Nepal, the land is the most valuable natural resource, providing 90 percent of the population with food, fiber, fodder, and timber. Agroforestry practices can increase land productivity, thereby contributing to the communal welfare of rural areas (Shrestha et al. 2020) and providing stable green employment opportunities. The Nepalese government is currently focusing on launching agroforestry programs in rural areas to improve rural livelihoods (Puri 2020).

Farmers in Nepal have been using their experiences to grow trees combined with crops and livestock for centuries (Paudel et al., 2021). Agroforestry practices in Nepal can be classified as (i) farm-based, which include home gardens and trees grown on agricultural fields, and (ii) forest-based, which includes agricultural activities linked to forests (Khadka et al., 2021). Nepal's forest area is dwindling, as are forest-related products that significantly impact the population relying on forest resources for a living. Agricultural activities provide a living for more than two-thirds of Nepalese households (Hernández et al., 2018). However, according to CBS 2012 statistics, at least one member of more than half of Nepalese households is employed abroad; while this may have remittance advantages, agriculture production is diminished as many families abandon agricultural methods (Cedamon et al. 2017). Land production has also been impacted by sedimentation and floods in the terai, as well as soil erosion and landslides in the highlands. The adoption of agroforestry has been advocated as a primary alternative in

Nepal for overcoming the demand and supply gap for forest-based goods (Bhattarai et al. 2020), along with other sustainable methods of boosting land potential and productivity (Kidd and Pimentel 1992). Dhakal et al. (2012) stated that infrastructure improvement, along with efficient institutional assistance, has a favorable impact on agricultural adoption in Nepal's terai areas. Many studies have assessed agroforestry adoption in tropics households (Mercer 2004; Meijer et al. 2015). While traditional studies of agroforestry potential have focused on agroforestry and forestry trends and practices, GIS is a relatively new data collection approach with great promise in the Nepalese context. Compared to traditional approaches, using scientific assessment tools to evaluate land resources not only aids in better planning and management but is also less costly and time-consuming (Ahmad et al., 2017). Kihoro, in Kenya, used a multi-criteria evaluation and GIS application to investigate land suitability for rice growing sites (Raza et al. 2018). Ritung et al. (2007) used remote sensing and GIS to examine land suitability for various agroforestry species in Aceh Barat, Indonesia, following FAO guidelines. Dengiz (2013) used GIS to investigate land suitability for rice cultivation in Cankiri-Kizilirmak, Turkey. In the present scenario, research carried out in the study area followed the conventional method and faced time and budget limitations. Thus, the objective of this study is to operate on remote sensing and GIS models to assess the agroforestry potential and status of the Kanchanpur District, Nepal. Policy developers or government agencies working in agroforestry and rural development need such data to understand and implement at a different level of project execution within the limited budget and time.

MATERIAL AND METHODS

Study area

The total geographic area of the study area is 1,610 square kilometers, and its elevation range confines from 176 meters to 1,528 meters above sea level (asl) (https://knoema.com/atlas/Nepal/Land-area). The district is located in a humid subtropical climate. The district's average temperature ranges from 10°C (winter) to 30 °C (summer)(https://www.worldweatheronline.com/kanchanpur-weather/np.aspx). The district receives 1,500 mm of annual rainfall (http://mecometer.com/whats/nepal/average-yearly-precipitation). The forest in this area is described as a low tropical *Shorea robusta* Gaertn. (Sal) and mixed hardwood forest (Sudhakar et al. 2018) with excellent natural regeneration and composition of trees that vary moisture accordingly due to aspect and slope variation. The soil is clay loam, light to medium textured, and supports rice, maize, and wheat, as well as horticulture crops like mango (*Mangifera indica* L.), banana (*Musa* genus), lemon (*Citrus ×limon* (L.) Burm.fil.), and litchi (*Litchi chinensis* Sonn.). Tree species characterized as fast-growing such as Shisham (*Dalbergia sissoo* Roxb. ex DC.), Semal (*Bombax ceiba* L.), and Masala (*Eucalyptus camaldulensis Dehnh.*), support the area (*Tectona grandis* L.f.). The rearing of cattle, such as buffaloes, goats, sheep, and pigs, is quite common, whereas poultry is greatly aided by integrating farming (Paudyal 2011).

Data collection

The data used in determining agroforestry potential were soil fertility, slope, rainfall, NDVI, wetness index, and elevation.

Soil fertility: The dominant presence of nitrogen (N), phosphorus (P), and potassium (K) in the soil results in high soil fertility, which the plants require in large amounts for their growth. Furthermore, the availability of nutrients to plants/crops is affected by the pH range of the soil. In contrast, an adequate soil organic carbon percent helps to improve the soil structure resulting in a higher release of nutrients available to plants for growth. The National Agriculture Research Council's (https://soil.narc.gov.np/soil/soilmap) soil maps of nitrogen, phosphorus, potassium, organic carbon, and pH status of the Kanchanpur District were used in this study to determine the soil fertility status.

Slope: The rate at which the elevation of the land changes per unit distance is known as slope. Water flows faster down steeper slopes. Flowing water has higher kinetic energy than still water, affecting aquatic habitats' stability. Plants thrive on gentle slopes because the water stays there for a long time and provides sufficient moisture required. As a result, gentle slopes are preferred for agroforestry over steep slopes. The aster DEM (https://www.usgs.gov/centers/eros/science/aster-global-digital-elevation-model) from the USGS portal was used to calculate the slope.

Rainfall: Rainfall serves as an essential parameter; its spatial variation positively correlates with the FAO's plant growth metric for land resource assessment. Spatial rainfall patterns (continuous surface) were generated in ArcGIS for average rainfall of 15 years using the Kriging interpolation method. Rainfall data from 2000 to 2015 was downloaded from Climatic Research Unit (https://crudata.uea.ac.uk/cru/data/hrg).

Normalized Difference Vegetation Index: The Normalized Difference Vegetation Index (NDVI) is a widely preferred vegetation index that accurately reflects vegetation health and vigor from remote sensing data (Gomes et al. 2017) and can be used to map agroforestry suitability successfully. It's also used to determine the relationship between NDVI and vegetation density. The lower the extent of erosion due to high vegetation vigor, the higher the NDVI value (Stanton et al., 2017). It can be found at https://www.usgs.gov/centers/eros/science/aster-global-digital-elevation-model.

Wetness Index: Crop growth and agricultural production require moisture in the soil. As a result, it creates an ideal environment for agroforestry. Landsat-8 satellite data, with an acquisition date of 1 December 2019, was used to prepare the wetness map of the study area. In addition, data on rainfall from 2000 to 2015 AD was downloaded.

Elevation: Elevation is a significant factor that affects plant growth. As the elevation rises, the temperature and vegetation decrease, resulting in the concept of a tree line.

The temperature of the air has a significant impact on the growth rates of trees. It is directly associated with photosynthesis and the respiration process, as well as influencing plant tissue temperature. The aster DEM calculated the slope (https://www.usgs.gov/centers/eros/science/aster-global-digital-elevation-model) from the USGS portal.

Data analysis

Soil fertility mapping parameters

The different soil-related maps were first rectified, and all soil polygon categories were fed into the GIS domain (Ahmad et al., 2017). Then, the soil fertility status map (Figure 3) was created by combining the nitrogen, phosphorus, potassium, organic carbon, soil pH, and sulfur availability map in a GIS modeling concept assigning equal weight and various ranks to each theme.

SF= 16.67% N+ 16.67% P+ 16.67% K+ 16.67% Oc+ 16.67% pH+ 16.67% S

Where, SF: Soil fertility, N: Nitrogen, P: Phosphorus, K: Potassium, Oc: Organic carbon content, pH: Soil pH, and S: sulfur.

Agroforestry potential mapping

The agroforestry potential map was generated by integrating soil fertility, slope, rainfall, NDVI, soil wetness, and elevation maps in the GIS modeling concept, assigning various weights and ranks to each theme.

Ap= 30% Sf+30% S+10% R+10% NDVI+10% Sw+10% E

Where: Ap: Agroforestry potential, S: slope, R: Rainfall, NDVI: Normalized Difference Vegetation Index, Sw: Soil wetness, and E: Elevation

The overall flow chart of the soil fertility analysis is shown in Figure 2.

The overall flow chart of the potential agroforestry analysis is shown in Figure 3.

Validation of result

Comparing classification against ground truth data to see how well the classification represents true geographical reference data is an accurate assessment. In assessing the classification accuracy, 50 ground truth positions were taken from the final agroforestry potential map by categorizing overall land into good (very high and high) and medium and bad(low and very low) potential agroforestry categories with the geographic coordinate of 30 and 20 respectively and applied it in the Google Earth images of 2021. The assessment was carried out using a confusion matrix, with the Kappa coefficient and overall accuracy calculated. The classification accuracy was calculated by dividing correctly categorized pixels by the total number of pixels. Furthermore, the accuracy of users and producers was determined to classify the accuracy of specific classes (Bharatkar and Patel 2013). Results are demonstrated using Table 4.

Overall accuracy (%) = (Number of correct pixels /Total number of pixels) $*$ 100

Users' accuracy (%) = (pixels classified correctly/ Total classified pixels) $*$ 100

Producers' accuracy (%) = (pixels classified correctly/ Total reference pixels) $*$ 100

Kappa coefficient (K) = (Po −Pe)/(1−Pe)

Where: Po: Proportion of pixels classified correctly and Pe: Proportion of pixels classified correctly expected by chance.

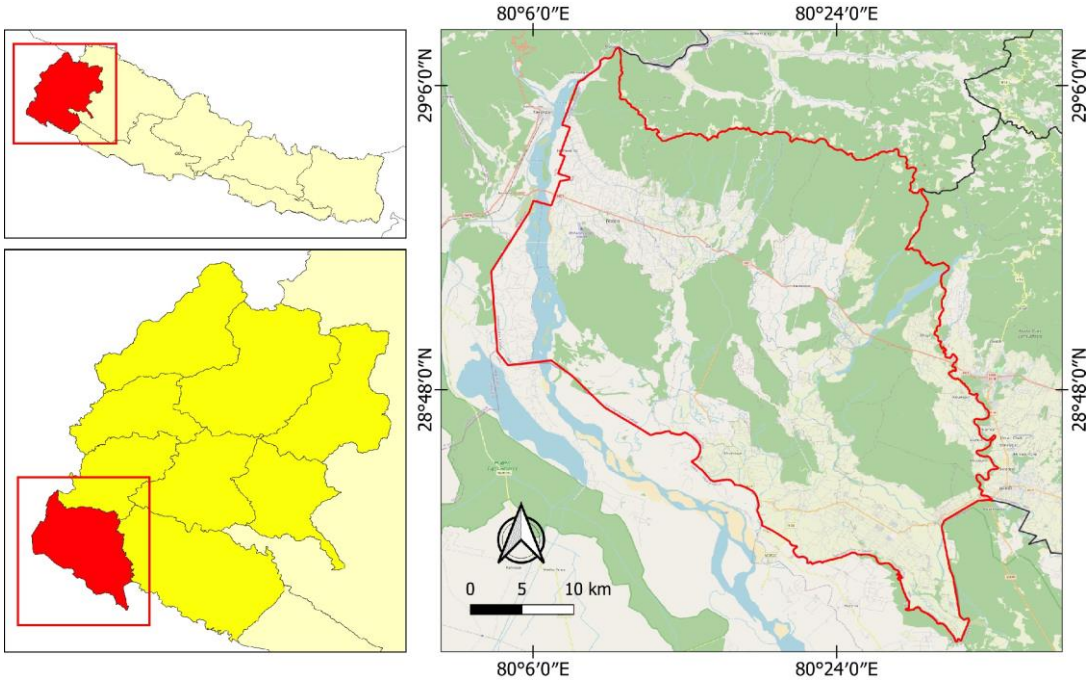

Figure 1. Map of study area showing Kanchanpur District, Nepal

Table 1. Collected datasets in the study

Dataset	File type	Data type	Spatial resolution	Sources
Study area boundary	Shp	Polygon		Department of Land Management and achieve, Nepal
Soil Data (N, P, K, Ph, Organic carbon)	HDF	Raster	30 m	National Agriculture Research Council
ASTER DEM	Tiff	Raster	30 m	USGS Earth explorer
NDVI	Tiff	Raster	30 m	USGS Earth explorer
Soil Wetness	HDF	Raster	30 m	USGS Earth explorer
Rainfall data	NetCDF	Raster		Climatic Research Unit

Table 2. Weight, value, and rating assigned to determine soil fertility

Soil map	Weights %	Value/Description	Ranks	Suitability
Nitrogen	16.67%	0.05 - 0.10 %	2	Low
		0.10 - 0.15 %	3	Medium
		0.15 - 0.20 %	4	High
Phosphorous	16.67%	<6 kg/ha	1	Very low
		6- 12 kg/ha	2	Low
		12-18 kg/ha	3	Medium
		18-24 kg/ha	4	High
		24-30 kg/ ha	5	Very high
Potassium	16.67%	< 200 kg/ha	1	Very low
		200- 250 kg/ha	2	Low
		250- 300 kg/ha	3	Medium
		300 - 350 kg/ha	4	High
		>350 kg/ha	5	Very high
Organic carbon content (%)	16.67%	1.5- 2 %	1	Very low
		2- 2.5 %	2	Low
		2.5 - 3 %	3	Medium
		3- 3.5%	4	High
		3.5 - 4%	5	Very high
pH	16.67%	6 to 7	3	Medium
		7 to 8	4	High
		8 to 9	3	Medium
Sulphur	16.67%	<5 mg/kg	1	Very low
		5- 10 mg/kg	2	Low
		10- 15 mg/kg	3	Medium
		15- 20 mg/kg	4	High
		>20 mg/kg	5	Very high

Source: Ahmad et al. (2017) and Ritung et al. (2007)

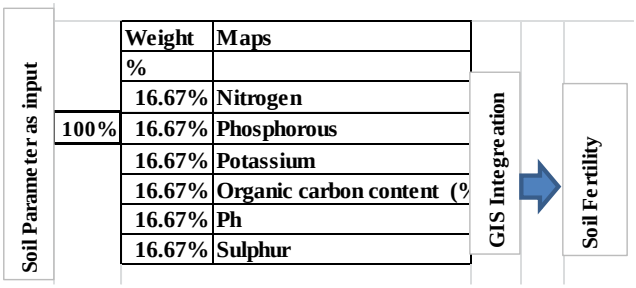

Figure 2. Flow chart of soil fertility analysis

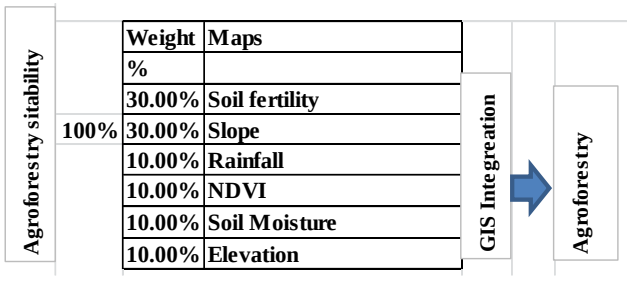

Figure 3. Flow chart of potential agroforestry analysis

Table 3. Weight, value, and rating assigned to determine agroforestry potential

Agroforestry suitability mapping	Weights %	Value/description	Ranks	Suitability
Soil fertility	30%	Weighted average output based on three categories	1	Very low
			2	Low
			3	Medium
			4	High
			5	Very high
Slope	30%	<2 degrees	5	Very high
		2-8 degrees	4	High
		8 - 16 degrees	3	Medium
		16 - 24 degrees	2	Low
		> 24 degrees	1	Very low
Rainfall	10%	< 1500 mm	3	Medium
		1500 mm	4	High
NDVI	10%	<0.4	1	Very low
		0.4 - 0.5	2	Low
		0.5 - 0.6	3	Medium
		0.6 - 0.7	4	High
		>0.7	5	Very high
Soil moisture	10%	Weighted average output based on three categories	2	Low
			3	Medium
			4	High
Elevation	10%	<200 m	5	Very high
		200 - 400 m	4	High
		400 - 674 m	3	Medium
		674 - 954 m	2	Low
		954 - 1489 m	1	Very low

Source: Ahmad et al. (2017) and Ritung et al. (2007)

RESULTS AND DISCUSSION

Soil fertility status map

All the soil nutrient parameters were accredited with equal weights to create the fertility map, resulting in a map that was 100 percent. Parameters were chosen based on findings of various related nutrient suitability research works, which were FAO-certified and used widely for plant growth. In creating soil fertility maps, soil nitrogen (N), phosphorus (P), potassium (K), soil organic carbon content (C), pH, and sulfur (S) were used. These parameters signify soil fertility and, more importantly, help ensure food security. For mapping different thematic maps, weights and ranks were assigned.

Agroforestry suitability mapping

Soil fertility map

All the parameters were assigned equal weights for preparing the nutrient availability map and then classified majorly into three groups: very high, high, medium, low, and very low.

Slope map

Aster DEM was used for slope extraction and then was reclassified into classes of <2°, 2-8°,8-16°, 16-24°>24° with the use of standard reclassification technique and finally ranked as 5, 4, 3, 2, and 1 with very high, high, medium, low and very low description.

Rainfall

Further classification of the map into two classes (<1500, 1500 mm) was carried out based on agroforestry suitability; and were ranked as 3 and 4 and detailed as medium and high, respectively.

Normalized Difference Vegetation Index (NDVI)

The high value of NDVI reflects the lesser erosion extent due to high vegetation vigor (Stanton et al., 2017). Therefore, the elevation was further reclassified into five subgroups Very Low (<0.4), Low (0.4-0.5), Medium (0.5-0.6), High (0.6-0.7), and Very High (>0.7).

Wetness index

The wetness value is classified into three classes and described as low, medium, and high based on their agroforestry suitability.

Elevation

The elevation was reclassified into five subgroups. First, the new values of our findings were assigned based on their agroforestry suitability, then ranked as 5, 4, 3, 2, and 1 accordingly, and finally described as very high, high, medium, low, and very low, respectively.

Agroforestry potential map

Factors contributing toward the agroforestry potentiality are Soil fertility [30], slope [30], Rainfall [10], NDVI [10], Soil wetness [10], and elevation [10], whose weights were scientifically chosen and are based upon the empirical results of various findings. For example, agroforestry suitability mapping for the Kanchanpur District of Sudurpaschim province, Nepal, showed 76.14% as very high suitable, 3.12% as high suitable, 13.89% as medium suitable, 5.67% as low suitable, and 1.15% as very low suitable.

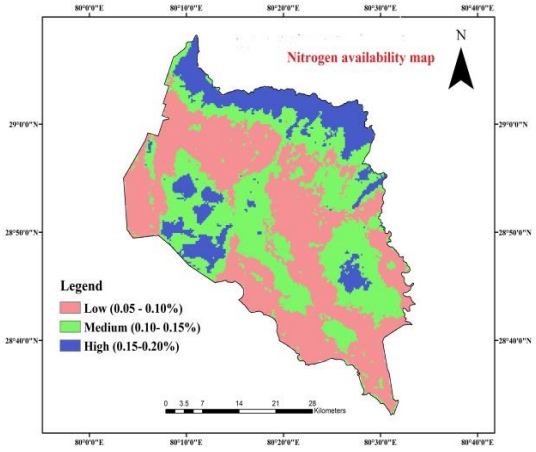

Figure 4. Nitrogen availability map

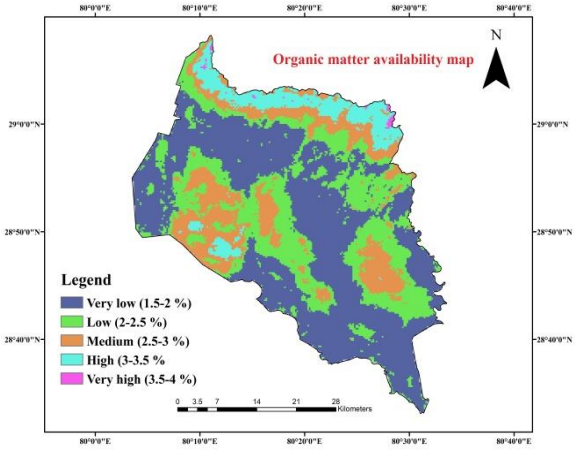

Figure 7. Organic matter availability map

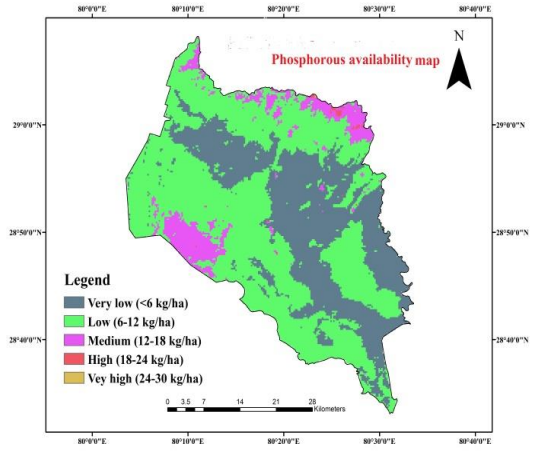

Figure 5. Phosphorous availability map

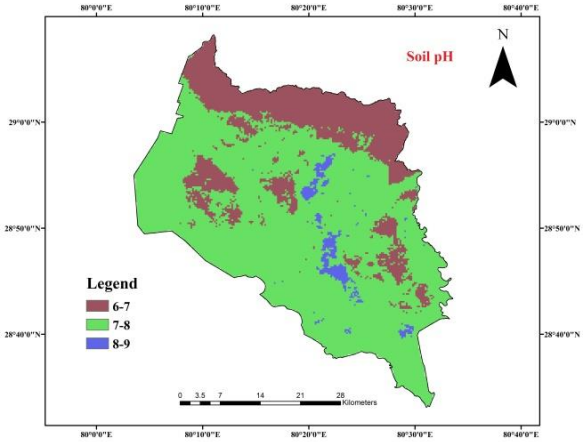

Figure 8. Soil pH level map

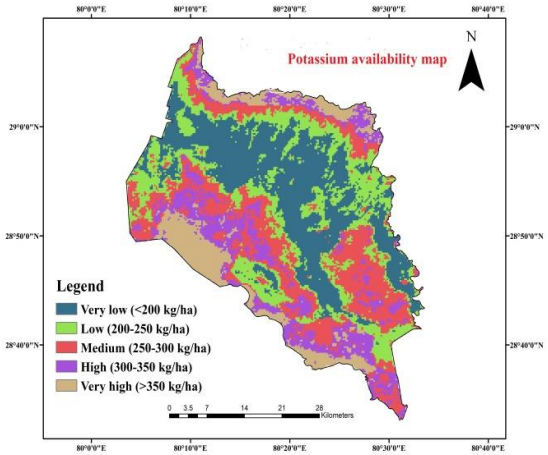

Figure 6. Potassium availability map

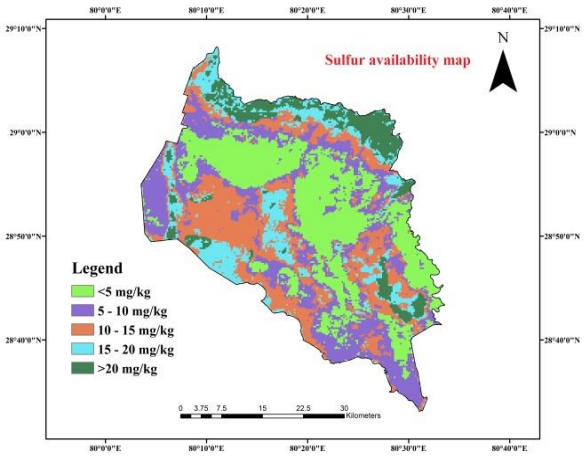

Figure 9. Sulfur availability map

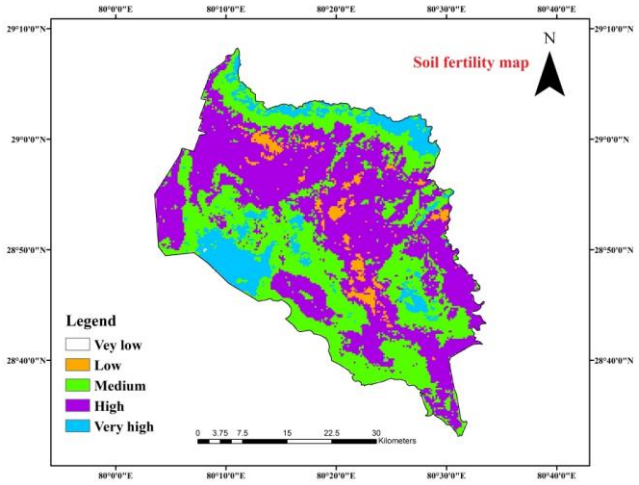

Figure 10. Soil fertility map

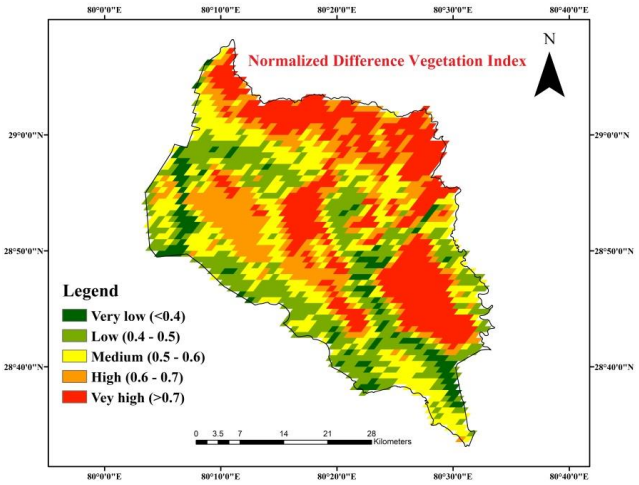

Figure 13. NDVI map

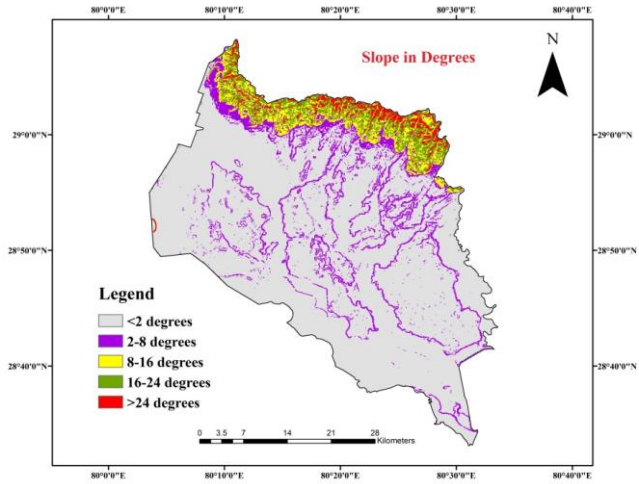

Figure 11. Slope map

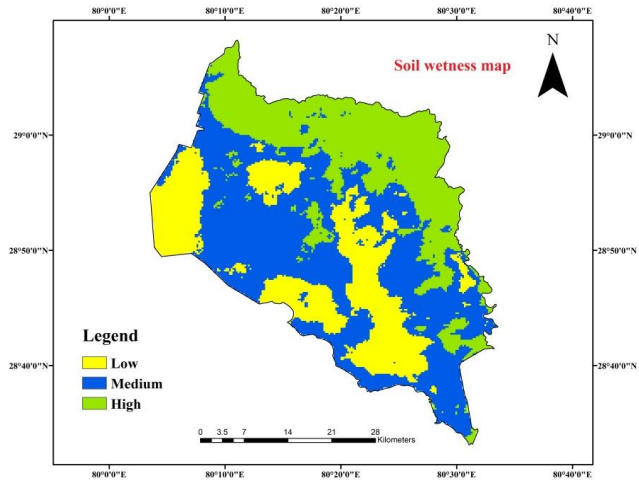

Figure 14. Wetness map

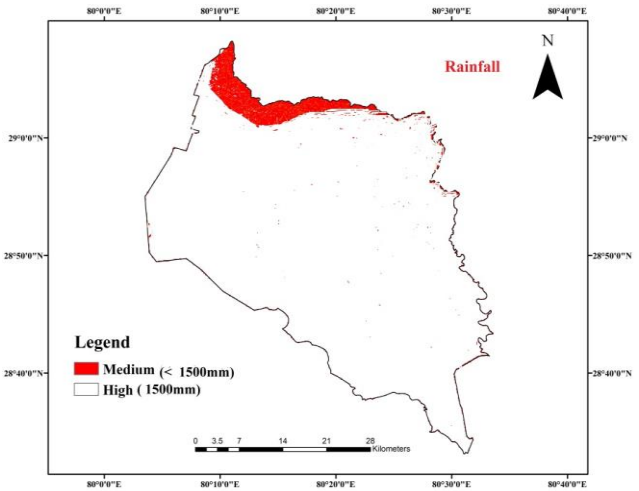

Figure 12. Rainfall map

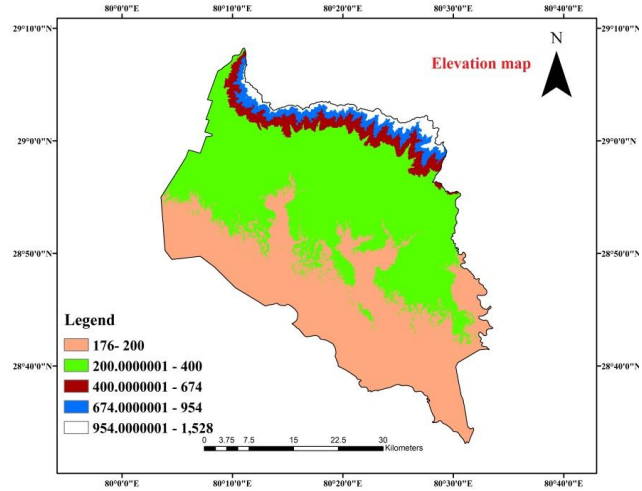

Figure 15. Elevation map

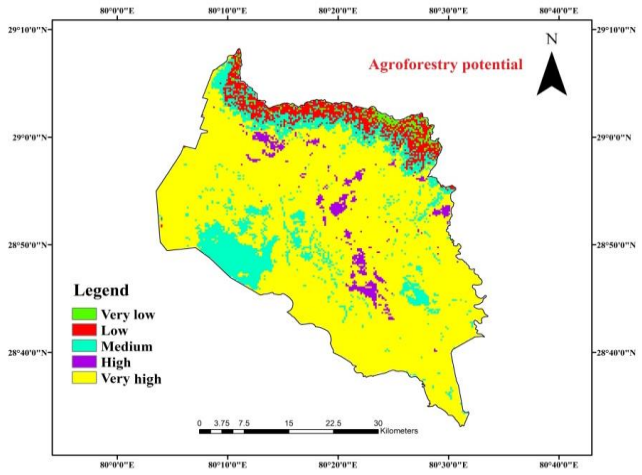

Figure 16. Agroforestry potential map

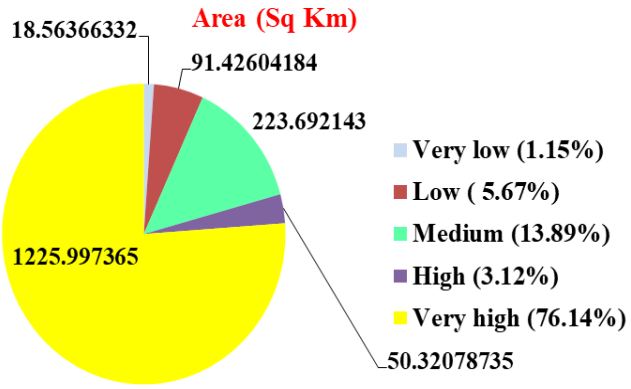

Figure 17. Agroforestry potential area

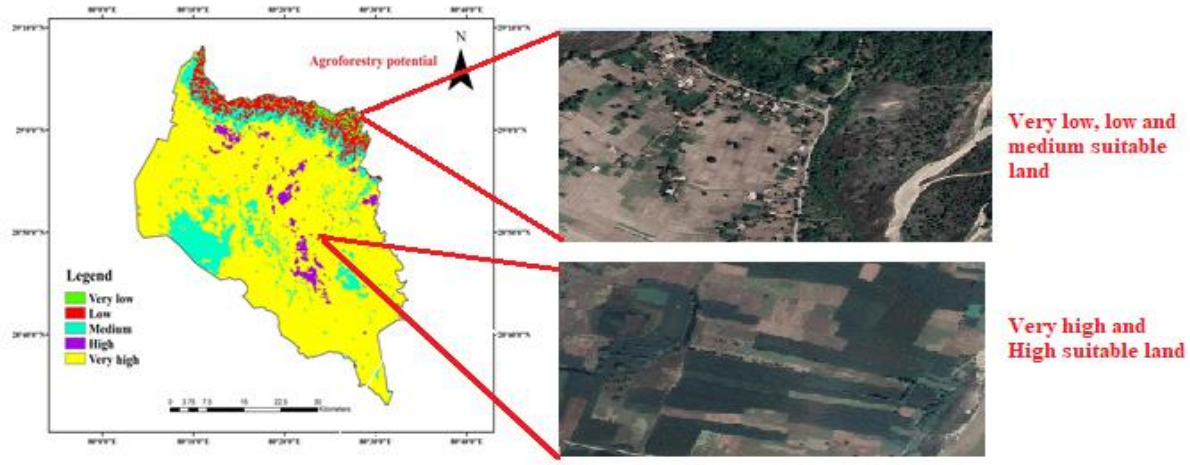

Figure 18. Accuracy assessment for agroforestry suitability map

Table 4. Ground truth data, accuracy, and Kappa coefficient

Ground truth	Good	Medium and bad	Undefined*	Total	User's accuracy(%)
Good	22	3	5	30	73.33333333
Medium and bad	1	13	6	20	65
Total	23	16	11	50	
Producers' accuracy (%)	95.65217391	81.25			
Kappa coefficient	0.67				Overall accuracy=70%

Note: *land conditions that are unclear to distinguish. The overall accuracy was 70%, while the kappa coefficient was 0.67. Since the classified maps' Kappa value was within 0.61-0.8, they are substantial and meet the accuracy assessment. (Note: According to Landis et al., 1977 considers 0-0.20 as slight, 0.21-0.40 as fair, 0.41- 0.60 as moderate, 0.61-0.80 as substantial, and 0.81-1 as almost perfect. Fleiss considers kappa > 0.75 as excellent, 0.40-0.75 as fair to good, and < 0.40 as poor)

Discussion

Agroforestry planning in tree/crop harvesting is intricately associated with agro-climatic factors (Ekka et al., 2020) and can be defined by determining agroforestry suitability (Ahmad et al., 2021). Soil fertility, slope, elevation, annual rainfall pattern, wetness, NDVI, Organic matter, and pH all play a role in an area's agroforestry suitability. Nitrogen, phosphorus, sulfur, organic matter, and pH affect soil fertility. Therefore, high agroforestry suitability is characterized by high soil fertility, high annual rainfall, high wetness, high NDVI, and low slope and elevation. Generally, hills have harsh slopes and terrain, so in terms of slope, agroforestry suitability is low compared to the area with moderate and low slopes. That is because hills have low water holding capacity and, as a result, the wetness level of the soil.

The agroforestry suitability mapping for the Kanchanpur District of Sudurpaschim province, Nepal, showed 1225 sq km (76.14%) area with very high suitability, 50.32 sq km (3.12%) area with high suitability, 223.69 sq. km (13.89%) area, with medium suitability, 91.42 sq km (5.67%) with low suitability and 18.56 sq km (1.15%) with very low suitability. The high-priority regions were discovered in open areas with abundant soil nutrients and adequate wetness, high rainfall, a moderate or low slope, and elevation, which all contribute to ideal plant growth conditions. They are primarily found in the southeast part of the study area. They are best suited for paddy crop cultivation due to suitable water and moisture availability during the rainy season. Medium agroforestry adaptability areas were common in moderate soil nutrients; high to moderate wetness, high to average rainfall, low to moderate slope, and low to medium elevation provided moderately favorable conditions for plant growth, accounting for about 13.89 percent of the entire research area. These areas are highly suitable for silvi-pastoral practices; soil binder grasses are likely to produce the desired results, as Ahmad et al. (2017) mentioned. The northwestern part exhibits harsh slope conditions, resulting in low agroforestry suitability. According to Ahmad et al. (2017), the lands suitable for agroforestry are found closer to rivers/lowland areas because of their high soil fertility and abundant soil wetness. In contrast, the soil in the southwestern part of the study areas is less suitable for agroforestry because of its low to medium soil fertility and low wetness, which contradicts our findings. Considering the site condition of the study region, several agroforestry systems such as Agri-Horti silviculture, Agri-silviculture, Silvi-pastoral, and agro-Silvi-pastoral can be effectively utilized. Waterlogged tree species such as *Albizia procera* (Roxb.) Benth. (white siris), *Butea monosperma* (Lam.) Kuntze (Palash), *Syzygium cumini* (L.) Skeels, *Terminalia arjuna* (Roxb.) Wight & Arn., and *Anthocephalus cadamba* (Roxb.) Miq. can be grown, whereas unfertile land tree species such as *D. sissoo*, *Gmelina arborea* Roxb. ex Sm., *Madhuca indica* J.F.Gmel., *Albizia lebbeck* (L.) Benth., *Ziziphus jujuba* Mill., and *Acacia catechu* (L.f.) Willd. can be grown. In addition, tree species such as *Azadirachta indica* A.Juss., *Pongamia pinnata* (L.) Pierre, *T. arjuna, A. procera, A. lebbeck*, and *Acacia auriculiformis* A.Cunn. ex Benth. can be grown in alkaline soil (Ahmad et al., 2021). The multipurpose leguminous tree species can be raised in field bunds to enhance the soil fertility of the land (Jhariya et al., 2018). A highly suitable landscape can be planned for the Agri-Silvi horticulture system based on the farmer's socio-economic needs with vegetables such as brinjal (*Solanum melongena* L.), cabbage (*Brassica oleracea* var. *capitata*), cauliflower (*Brassica oleracea* var. *botrytis*), okra (*Abelmoschus esculentus*), potato (*Solanum tuberosum* L.), tomato (*Solanum lycopersicum* L.) (Pandit et al. 2014). Medium areas can be preferred for an agri-silviculture practice, provided with an adequate irrigational facility during the off-monsoon season to ensure suitable soil moisture for trees and crops (Ahmad et al., 2021).

In conclusion, this study drew on various themes from numerous sources of information connected to multiple agroforestry systems. Computer-based varied datasets and their logical analysis utilizing geospatial tools such as rs and gis have substantially improved the decision-making process for users such as landowners, foresters, and farmers to meet the aims of agroforestry suitability mapping. The government has launched several programs for the impoverished and tribal people/farmers to implement integrated land management plans to maximize agroforestry potential. It is necessary to identify potentially suitable land for agroforestry and develop or redirect existing programs to utilize it considerably, improving livelihood. Agroforestry is similar to hanging fruits that must be harvested scientifically.

Agroforestry is regarded as the backbone of marginal farming for self-sufficiency and sustainability. It can tackle the most severe food security concerns, while environmental security is a crucial advantage of agroforestry systems. The results show that three-fourths of the total land in the research region has a high potential for agroforestry practice because it falls in the very high appropriate category (s1), provided restrictions such as soil moisture, enough funding, and proper technical assistance are addressed. The findings and suitability map may be implemented into many existing and future land-based management programs, resulting in long-term advantages to rural and tribal people in poverty alleviation through increased livelihood choices. Assessing the land's capability and potential for appropriateness for various crop/tree productivity is necessary. Policymakers must incorporate such data into future land planning and management to ensure crop and tree appropriateness. Even though topographic shadows in satellite images, like layover and forecasting effect, were a significant hindrance in image classification, this research describes the tremendous ability of remote sensing (coarse resolution data) as well as spatial dimensions of land, soil, climate, and topographical data integration under gis domain, demonstrating its enormous potential for evaluating land capability and economic output.

ACKNOWLEDGEMENTS

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Estimation of carbon stock and emission of community forests in Eastern Amhara, Ethiopia

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Abstract. *Biadgligne A, Gobezie T, Mohammed A, Feleke E. 2022. Estimation of carbon stock and emission of community forests in Eastern Amhara, Ethiopia. Asian J For 6: 74-82.* Carbon emission resulting from deforestation and forest degradation contributes to climate change. Halting deforestation is, therefore, one strategy to mitigate the changing climate. As the global carbon market develops, an opportunity to halt deforestation can be contributed by community forests as a win-win solution for climate change mitigation and livelihood provision, yet knowing the carbon stock of the forest is important to enhance the bargaining power of the community to get carbon finance. Thus, a case study was conducted to quantify carbon stocks and emissions from three community forests (i.e., Asha-Guba, Jemely, and Beshilo) in Eastern Amhara, Ethiopia. Stratified systematic sample quadrate methods were used, and a total of 57 equally spaced nested square quadrats were laid for the measurement of carbon density. Carbon pools, including above-ground living biomass, dead wood, surface litter, belowground root biomass, soil organic carbon, and harvested wood product, were accounted for the estimation of site-level carbon density (t ha^{-1}) and carbon dioxide equivalent (CO_2e) emission. There was high variability in the estimated mean carbon density and CO_2e emission across the three community forests. The highest carbon density was recorded in the Asha-Guba community forest with 124.27 ± 8.29 t ha^{-1}, followed by Jemely and Beshilo forests with 91.24 ± 3.18 t ha^{-1} and 73.55 ± 3.13 t ha^{-1}, respectively. The largest proportion (59-63%) of carbon was stored in the soil pool, followed by the above-ground biomass (27-32%), while that in dead organic matter was insignificant. The community forests currently stored total carbon stocks of 57,612.14 ± 13.81ton (210,860.43 CO_2e). To ensure the sustainable management of the forests, long-term finance and investment must be introduced urgently.

Keywords: Biomass, carbon emission, carbon pools, community forest, deforestation

INTRODUCTION

Forest is one of the inherent and critical components of the earth's surface. It covers 31 percent of the earth's land surface and contains most of the terrestrial biodiversity (FAO 2022). Forests also play an important role in regulating the global climate, preventing land degradation, and contributing to environmental stability (De Groot et al. 2010; Nugroho et al. 2022). In addition, it is a home for half of all life on earth and a source of livelihood for more than 1.4 billion of the world's poor (Kendie et al. 2021). Nonetheless, many forests around the world are threatened by deforestation and forest degradation due to anthropogenic factors. As a result, the world's forests declined by 3%, from 4128 million hectares in 1990 to 3999 million hectares in 2015 (Keenan et al. 2015). Forest Resources Assessment (FRA) 2020 estimated that between 1990 and 2020, around 420 million ha of forest has been deforested and converted to other land uses. Although the rate declined over the period, deforestation was still estimated at 10 million ha per year in 2015-2020 (approximately 0.25 percent per year) (FAO 2020).

Forest carbon stocks in the world's forest biomass decreased by an estimated 0.5 Giga tons annually from 2005-2010 (Poulter et al. 2010). Globally, deforestation contributes to 20% of anthropogenic GHGs emissions (Stern 2006; Le Quéré et al. 2009). In Africa, about 70% of GHGs emission is caused by deforestation (Gibbs et al. 2007). Despite causing carbon emissions due to deforestation and forest degradation, forests have the potential to contribute to 50% GHGs mitigation (Eggelston et al. 2006). For instance, forest ecosystems in the conterminous United States store 52.0 Pg C across all pools, and carbon storage increased by 2.4 Pg C at an annualized rate of 126 Tg C $year^{-1}$ (Sleeter et al. 2022). Considering the importance of the forest in balancing CO_2 in the earth's atmosphere (Thompson et al. 2013), there is a pressing need to quantify the sources and sinks of carbon contained in the forest. In this regard, forest management becomes the key factor in whether a forest acts as a source or sink of carbon.

Sustainable forest management positively contributes to regulating climate change by sequestering CO_2 from the atmosphere while helping to meet future demand for materials and ecosystem services and support greener and circular economies, particularly at the local level (Vignola et al. 2009; Kumar et al. 2016; FAO 2022). Despite the potential for climate change mitigation, managing forests sustainably is an enormous challenge. This is because a quarter of forests in developing countries are under community control (World Bank 2008). There are variations in terminologies, although they have similarities

in concepts, for instance, social forestry (Danks and Fortmann 2004); Joint Forest Management (Poffenberger and McGean 1998); Community-Based Forest Management (Mbuvi and Kungu 2021); Community-Based Forestry (Gauld 2000), and so on. In Ethiopia, a community forest is a forest that is conserved, developed, utilized, and administered by the community (FDRE 2018). In this context, the quality of local-level institutions is one of the determinants of forest carbon sequestration (Beyene et al. 2013).

An increasing interest in carbon trading and offsetting provides an opportunity for better forest management, a win-win solution for climate change mitigation and livelihood provision for forest-based communities. This can manifest by establishing carbon reserves in the forest ecosystem through afforestation and reforestation in a degraded landscape. Such efforts could be implemented with carbon trading mechanisms in a community forest. Nonetheless, the magnitude of carbon stock should be quantified to enact a benefit-sharing mechanism under a carbon trading scheme in a community forest (Pandey 2002). In Ethiopia, there is a great prospect of reducing 50% GHG emission between 2010 and 2030 from forest-based activities. However, the baseline information on the forest carbon stock is lacking. Specifically, no studies have been conducted to assess carbon stocks in community forests. Therefore, reliable and up-to-date quantification of the sources, sinks, and carbon changes is essential to assess the potential of community forests in reducing carbon emissions (Schelhas et al. 2010). Knowing the carbon stock of the forest enhances the community's bargaining power in the global carbon market. Thus, it is expected to provide meaningful information for local management decisions and planning.

This study is designed to estimate the organic carbon stocks of the community forests in Eastern Amhara, Ethiopia, and to set a baseline carbon dioxide emission level for future monitoring and evaluation activities. In this study, stratified systematic sample quadrate methods were used. A total of 57 equally spaced nested square quadrates were laid for the measurement of carbon density. Carbon pools, including above-ground living biomass, dead wood, surface litter, belowground root biomass, soil organic carbon, and harvested wood product, were considered to estimate site level carbon density (t Cha^{-1}) and CO_2e emission.

MATERIALS AND METHODS

Study area description

The study was conducted in Eastern Amhara, Ethiopia, extends between 11°7'30" to 11°26'20" N and from 39°18'50" to 39°37'00" E (Figure 1).

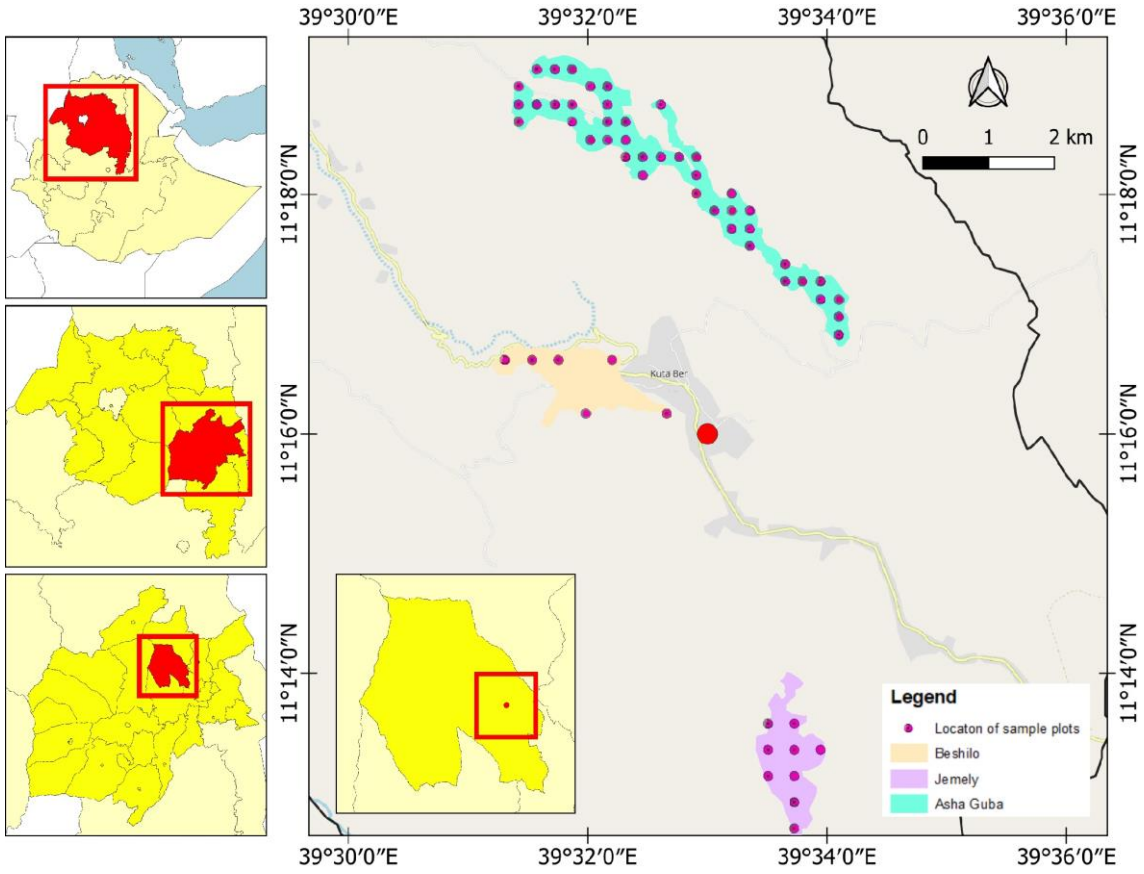

Figure 1. Map of study area and sample sites in Eastern Amhara, Ethiopia

Table 1. Determination and allocation of sample size in the studied area

Statistical parameters	Community forest			Total
	Asha-Guba CF	Beshilo CF	Jemely CF	
Forest area (ha)	322	78	130	530
Quadrat size (ha)	0.25	0.25	0.25	
Mean biomass carbon density (t ha^{-1})	85	61.5	67	
(SD) Standard deviation	22.7	5.5	3.4	
Ni (total no. of quadrat)	1288	312	520	2120
Desired precision (90%)				0.9
Permissible error (100-90= ±10%)	±8.5	±6.1	±6.7	
t value at 95% confidence level (~ 1.96)	1.96	1.96	1.96	
Coefficient of variation in % (CV)	26.71	8.94	5.07	
n (sample size)	38	5	8	51
10% contingency	4	1	1	6
Sampling units allocated to stratum	42	6	9	57

The topography is dominated by a chain of a mountain, mountain ridges, and valley bottom (Kasssaw 2010). The total population of Kutaber district was 126,805 (male = 62,918; female = 63,887) of which only 5.18% live in the urban area and 94.82% live in the rural area (CSA 2007). Mixed agriculture remains the main livelihood activity (Mekuria et al. 2020). An agricultural landscape dominated the study area, while only a small portion of the area was covered by forest (Kasssaw 2010). The local community depends on the forest for energy and construction materials (KOA 2021).

Research design and sample size determination and allocation

The study object includes all community forests in eastern Amhara. Among them, purposively selected Asha-Guba, Beshilo, and Jemely community forests. Systematic and purposive sampling with stratification methods were employed to obtain representative samples from the targeted studied area (Pandey 2002). First, the forest area was stratified based on dominant tree species composition, forest origin, and geographic location to draw a sample from non-overlapping sub-populations. Second, a precision level of ± 10% of the mean with a 95% confidence interval was implemented to get a reliable estimate. Third, the variance and standard deviation between the means of biomass carbon (t ha^{-1}) were computed from subjectively selected nine plots of an equal area (Pearson and Brown 2005). Thus, based on the data obtained in the preliminary survey, the sample size and sampling procedure used in this study are shown in Table 1.

Vegetation and soil data were collected during the dry season of the year 2020. A nested square sample quadrat was chosen for a simultaneous inventory of different carbon pools. In this design, the main quadrat (50 m x 50 m), the mid-sized quadrat (10 m x 10 m), and the small quadrats (1 m x 1 m) were established for the measurement of the tree, shrubs, and litter plus herbaceous vegetation, respectively. The sampling units were automated using the ArcGIS fishnet tool. Quadrats were laid starting from the northwest corner to the south, then proceeding to the southeast and towards the north. GPS was used to locate quadrats and meter tape was used to set quadrat dimensions, and nylon rope was used to demarcate the boundary.

In the main quadrat, the diameter of all trees (DBH ≥ 2 cm) was measured using a caliper, and tree height was estimated using a hypsometer, while in the mid-size quadrat (10 m x 10 m), shrubs having a collar diameter of 30 cm above the ground were measured its diameter and the values were recorded on a data collection sheet. Furthermore, in the small quadrat, soil parameters were collected from five circular pits (30 cm in depth and 30 cm in diameter) lying at the four corners and the center of the main quadrat. The 30 cm soil thickness was further classified into 3 layers to treat SOC in the top 0-10 cm, 10-20 cm, and the bottom 20-30 cm separately.

Data analysis

The ground data were coded and properly arranged before applying descriptive statistics such as mean, standard error of the mean, range, and ratio, and inferential analysis such as Pearson product-moment correlation using Statistical Package for Social Science version 20.1. Finally, the findings were presented using statistical tools like tables and figures to facilitate interpretation.

Forest carbon stock analysis

General and species-specific allometric equations (AE) can be used to estimate carbon in the forest ecosystem. General AE estimates of biomass are common equations applied over a large area (Houghton 2005) and were derived from many trees with a wide range of DBH (Brown 2002). However, generalized AE does not accurately predict above-ground biomass (Litton et al. 2006), leading to a bias in estimating biomass for a particular species. Therefore, species-specific AEs are used to predict tree and stand biomass based on easily measured tree variables such as height, diameter, and crown (Kangas and Maltamo 2006). Such equations are specific to species, sites, tree age, and management (Kairo et al. 2009), resulting in higher accuracy levels for biomass estimation and quantifying carbon. Studies in temperate and tropical regions have proven the advantages of species-specific biomass and volume allometry (Basuki et al. 2009). In addition, species-specific AE is preferred because tree species may differ greatly in tree architecture and wood gravity (Ketterings et al. 2001). The allometric equations used to estimate above-ground biomass in this study are shown in Table 2.

Table 2. Species specific allometric equations used in this study to calculate above-ground biomass (in kg)

Tree and shrubs species	Allometric equations	Reference
Eucalyptus globules	ABG = 0.0673* (WD*DBH2*Ht)0.976	Chave et al. (2014)
Cupressus lusitanica	AGB= Exp[-2.187 + (0.916 *ln(WD*DBH2*Ht))]	Chave et al. (2005)
Juniperous procera	AGB= 0.348 * DBH 0.57* Ht 0.032	Gereslassie et al. (2019)
Maytenus arbutifolia	AGB= 0.288 * WD 1.1864 * DBH 2.0649 * Ht 0.6096	Debela (2017)
Rosa abyssinica	AGB= 1.215 * WD 0.9726 * DBH 1.0817 * Ht -0.2603	Debela (2017)
Olea africana	AGB= (0.6806*DSH) + (0.0422*(DSH*exp2.7))	WBSPP (2005)
Acacia abyssinica	AGB= Exp[-2.409+ (0.9522 * ln (WD * DBH2 * Ht))]	Brown et al. (1989)
Psychoteria orophila	ln(AGB)= 2.160*ln(DSH)+0.796*ln(Ht)+ε	Dibaba (2018)
Allophylus abyssinicus	AGB= Exp[-2.557+ (0.94 * ln (WD2 * Ht)]	Dibaba (2018)
Tropical shrubs	AGB= Exp[-2.557+ (0.091 * DBH2.472)]	Kuyah et al. (2013)

Note: WD: Wood Density (kg/m^3), DBH: Diameter at breast height (cm), Ht: Total height of tree (meter), Exp: "e to the power of ", ln: Natural logarithm to the base 'e' (i.e., the value of 'e' ≡ 2.718) and DSH: diameter at stump height (cm)

The biomass of aboveground woody vegetation (DBH ≥ 2 cm) was estimated by combining forest inventory data with a species-specific allometric biomass regression model (Brown 2002; Houghton 2005; Chave et al. 2005, 2014; Gereslassie et al. 2019). Then, the biomass stock density of a sampling quadrat was converted to carbon stock densities after multiplication with the default carbon fraction of 0.47.

Below-ground root biomass carbon stocks were estimated based on a series of root-to-shoot ratios set for major forest types (Eggelston et al. 2006) as provided by (Cairns et al. 1997) below.

$$BGRB(kg) = Exp\left[1.0587 + \left(0.8836 * ln(ABGB)\right)\right]$$

The total biomass of dead wood (DW) was estimated by summing up the standing and felled dead wood (Pearson and Brown 2005). Then, the biomass of above-ground non-woody vegetation (< 2 cm DBH) and surface litter per 1 m^2 area was computed using the equation proposed by Pearson and Brown (2005), as shown below.

$$Dry\ Mass\ (Kg) = \frac{Sub\ Sample\ Dry\ Mass\ (kg)}{Sub\ Sample\ Fresh\ Mass\ (kg)} * Field\ Mass\ (kg)$$

Soil organic carbon analysis was carried out at Dessie Soil Testing and Fertility Management Center. In this laboratory, the Walkley-Black method was applied to estimate the concentrations of organic carbon in the soil. The soil organic carbon (t ha^{-1}) was thus computed from soil bulk density (BD), soil depth (D), and carbon concentration (C) following Pearson and Brown (2005) as below.

$$tC/ha = \left[\left(BD\ \left(\frac{g}{cm3}\right) x\ D\ (cm) x\ C\%\right] x\ 100\right.$$

The total carbon stock (TCS) was estimated by summing all carbon stored in each forest's carbon pools (i.e., above ground living tree biomass (ABGLTB) + above ground living non-tree biomass (ABGNTB) + below-ground root biomass (BGRB) + dead wood biomass (DW) + litter biomass (SL) + soil organic carbon (SOC)).

Setting baseline emission in community forests

Baseline emission refers to the carbon stocks or CO_2 equivalent GHG emission expected for a given time period. This is the sum of emission per year during the projection period under the baseline scenario. This involves a simple multiplication of the average tons of CO_2e emissions per hectare obtained from field inventory (i.e., Emission Factor) by the area deforested per year as shown in equation below.

$$Baseline\ Emission = \sum_{n=1}^{t}(AD * EF)$$

Where;
AD: Deforested area (ha/year) under baseline scenario
EF : Carbon stocks (tCO_2e/ha) in the forest
T : Projection life span (i.e., 2020 to 2030)

Reference Emission Level (REL) analysis

Setting REL or baseline emission involves a simple multiplication of the average tons of CO_2e carbon per hectare obtained from field inventory (Emission Factor) by the rate of deforestation, as shown below.

$$Overall\ Uncertainty\ (U\ \%) = \sqrt{(U\_Carbon)^2 + (U\_area)^2}$$

$$= \sqrt{\left(\frac{t*SEM}{\mu} * 100\right)^2 + (1 - \check{k})^2}$$

Where;
U-carbon %: Percentage uncertainty in the estimate of mean carbon density (t ha^{-1}), which is ½ (95% CI) *100/μ
95% CI = C density ± t*SEM
μ : The mean carbon density of the forests (t ha^{-1})
U-area (%): Percentage uncertainty in land cover change analysis

RESULTS AND DISCUSSION

Structure and basal area of community forests

In the study area, the total number of tree species observed were nine species of which three species (25%) were found in Asha-Guba, two species (16.7%) in Beshilo, and seven species (58%) were found in Jemely community forests. The DBH and height structure showed a pattern with relatively high frequency in the lower DBH class and gradually declining towards the higher DBH classes (Figure 2).

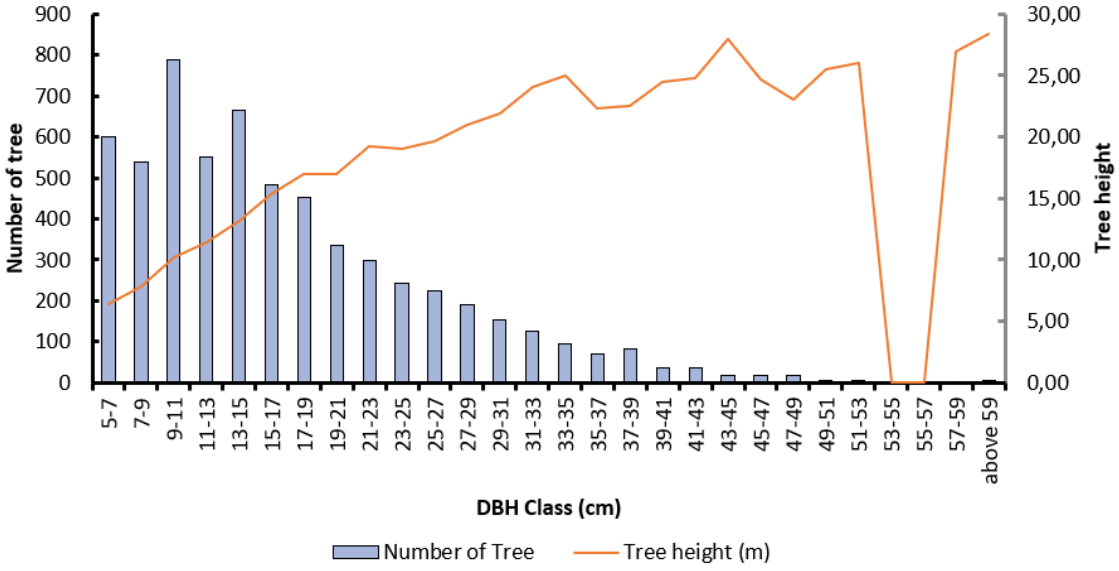

Figure 2. Tree species structure in across varying DBH class in the community forests in the studied area

Table 3. Total carbon stocks from various pools and its CO_2 equivalent in three community forests in Amhara, Ethiopia

Carbon pool		ABG		H	BGRB	DOM		Soil C	Total	CO_2e
		LT (t ha^{-1})	LS (t ha^{-1})	H (t ha^{-1})	LDR (t ha^{-1})	DW (t ha^{-1})	SL (t ha^{-1})	SOC (t ha^{-1})	(t ha^{-1})	
CF	Stat									
Asha-	M	43.01	0.71	0.2	10.5	1.04	0.06	68.75	124.27	485.46
Guba	SE	3.62	0.17	0.04	0.67	0.31	0.01	0.39	4.23	16.25
Jemely	M	13.37	1.47	0.01	3.56	0	0.12	72.71	91.24	336.94
	SE	0.83	0.44	0	0.14	0	0.03	0.77	1.22	3.89
Beshilo	M	3.31	0.18	0.03	1.34	0.11	0.1	68.47	73.55	275.32
	SE	0.56	0.1	0.01	0.14	0.06	0.02	0.77	1.17	3.45
Total	M	34.15	0.78	0.15	8.44	0.78	0.07	69.34	113.71	439.89
	SE	3.33	0.15	0.03	0.68	0.23	0.01	0.37	3.95	15.85

Notes: M: Mean; SE: Std. Error; ABG: Above ground biomass (LT: Living tree and LS: Living shrubs); BGRB: Below-ground root biomass (LDR: Live + Dead roots); H: herbaceous; DOM: Dead organic matter (SL: Surface litter; DW: Dead wood); CO_2e: carbon dioxide equivalent emissions

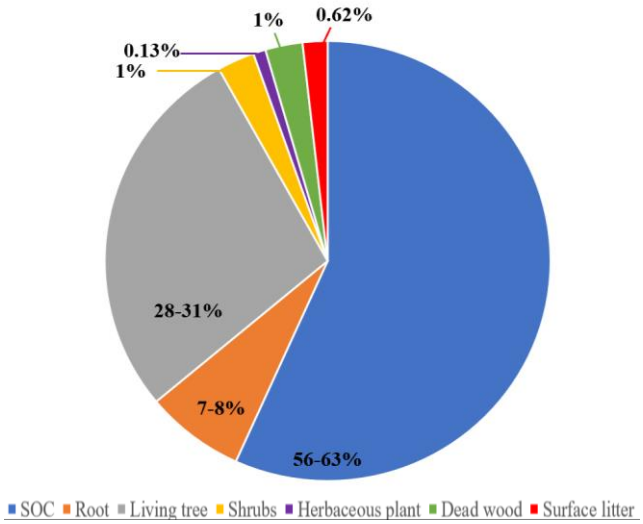

Figure 3. Proportion of estimated carbon stocks in various carbon pools in community forests in Amhara, Ethiopia

In line with the carbon stock of community forests

An estimated carbon stock in a unit area (t ha^{-1}) of the community forests is shown in Table 3. The mean carbon stock was estimated to be 124.27 ± 4.23 t ha^{-1} in Asha-Guba, 91.24 ± 1.22 t ha^{-1} in Jemely, and 73.55 ± 1.17 t ha^{-1} in the Beshilo community forest.

Aboveground and belowground biomass varied significantly among the community forests. Living tree biomass generally ranged from 3.86 t ha^{-1} in Beshilo to 210.1 t ha^{-1} in Asha-Guba, with the highest overall biomass of 72.65 ± 7.09 t ha$^{-1.}$ The highest proportion of ABG biomass (71%) was found in the living tree alone. Below-ground root biomass was thus computed from ABG biomass using the allometric equation as explained in the Methods. This resulted in below-ground root biomass of 17.94 t ha^{-1}, or 24% of the ABG biomass.

The largest proportion of carbon (Figure 3) was stored in the soil pool followed by AGB pool. The contribution of herbaceous, litter and non-tree woody vegetation carbon pools (together accounts 1.75% of the TCS).

Table 4. Reference emission level of three community forests in Amhara, Ethiopia under BAU scenario

Year	Forest area (ha)	Deforested area (AD) = Area*0.0193	Average emission factor (tCO_2e/ha) (a)	Anthropic Vegetation in Equilibrium (AVE) (tCO_2e/ha) (b)	Net emission (tCO_2e/ha) (a-b)	Baseline emission Ex-ante post-deforestation class tCO_2e Emission
Historic time	**530**					
2020	411.0	8.22	154	18	136	1117.92
2021	402.8	8.05	154	18	136	1094.80
2022	394.7	7.89	154	18	136	1073.04
2023	386.8	7.74	154	18	136	1052.64
2024	379.1	7.58	154	18	136	1030.88
2025	371.5	7.43	154	18	136	1010.48
2026	364.2	7.28	154	18	136	990.08
2027	356.8	7.13	154	18	136	969.68
2028	349.7	6.99	154	18	136	950.64
2029	342.7	6.85	154	18	136	931.60
2030	335.8	6.72	154	18	136	913.92
	329.20	81.8				11135.7

Estimated baseline emission of the community forests

Baseline emission refers to the carbon stocks or CO_2 equivalent GHG emission expected for a given time period. This is the sum of emission per year during the projection period under the baseline scenario. This involves a simple multiplication of the average tons of CO_2e emissions per hectare obtained from field inventory (Emission Factor) by the area deforested per year. Thus, to compute Emission Factor (tCO_2e ha^{-1}) in the pre-deforestation period, the amount of carbon estimated from harvested wood (HW), extracted through clear cutting and selective logging has been added to ABG biomass carbon which was 42.078 t ha^{-1}. The assumption is that all carbon in HW is oxidized in the removal year. Below-ground root carbon and SOC are disregarded in the computation because they were not easily subjected to deforestation as ABG pools. The average EF (tCO_2e/ha) was calculated for all forest sites together by considering the aggregate mean carbon stock density (Table 4).

concept of IPCC Good Practice Guidance (IPCC 2003), estimates of CO_2 emissions and carbon sequestrations have uncertainties associated with area and other activity data. In this study, uncertainty can arise both from land cover classifications and carbon stock estimation. Thus, the over-all uncertainty has been estimated by combining the two sources of uncertainties with simple error propagation as explained in the Methods. The calculation of oveall uncertainty resulted in a value of 13.5%, meaning that the annual rate of reference CO_2e GHG emissions extrapolated during the period 2020 to 2030 was 86.5% accurate.

Discussion

Structure and basal area of the forests

The analysis on forest structure revealed that the DBH class of 9-15 cm had higher frequency than that in the lower DBH 5-9 cm class. The DBH and height structure showed a pattern with relatively high frequency in the lower DBH class and gradually declining towards the higher DBH classes and vice versa for height (Figure 2). *Juniperus procera,* which was common across all forest sites, was observed in Jemely natural forest with importance value of 138. It was the basal area (8.21 m^2 ha^{-1}) that makes *Cupressus lusitanica* more dominant in Asha-Guba plantation than *Eucalyptus globulus* with a basal area of 5.54 m^2 ha^{-1}, having higher records of relative frequency and relative density than *C. lusitanica.* This was due to the inclusion of more *E. globules* coppice which had a lower relative dominancy value (33%) than *C. lusitanica* (non-coppicing species) having 49% dominancy.

The highest mean tree height (21.9 m) was observed in the Asha-Guba plantation and the lowest mean tree height (9.5 m) was in the Jemely natural forest. For the 55-57 cm DBH class, there was no record of the tree at all, while there were few old-growth trees above 59 cm. The graph in Figure 2 shows an almost positive relationship between DBH and height except for frequency. Medium-sized trees account for the largest share (66%) of stand structure at the study site, while very small trees (DBH = 0-30 cm) and very large trees (DBH >60 cm) contribute to less than 8.3% and 25.5% of the structure, respectively (Holtmann et al. 2021).

Carbon stock density of the forests

Tree species composition influences patterns of maximum forest biomass accumulation in the study area. Mixed tree species increase the storage of SOC and biomass accumulation in the forest (Augusto and Boča 2022). Of the total shrubs biomass, Jemely natural forest contributed higher mean biomass estimates of 3.12 ± 0.32 t/ha, compared to Asha-Guba (1.51) and Beshilo (0.39). The biomass with ranges of 0 to 9.75 t/ha shows that there are quadrats devoid of shrubs biomass in Beshilo and Asha-Guba plantation sites. These forests accumulated a lower amount of dead wood than Alpine and Atlantic forests, which were 6.09 and 3.53 Mg ha^{-1}, respectively (Alberdi et al. 2020). Hence, standing adult-tree account for more proportion of the total volume.

The results of this study support the findings of Beaulne et al. (2021), who reported that peat layers, with an average of 22.6-66.0 kg m^{-2}, store much more C than AGB and BGB of boreal forests in Canada (2.8-5.7 kg m^{-2}). Forest soil has the potential to store carbon and contribute to

mitigate GHGs. In total, soil contains about 3 times more carbon than the atmosphere and 4.5 times more carbon than living things. Hence, a relatively small increase in the proportion of soil carbon could make a significant contribution to reducing atmospheric carbon (Walcott et al. 2009).

Aboveground and belowground carbon biomass of the forests

The biomass of the study area was 94.38 ± 8.52 t ha^{-1}, with the minimum and maximum biomass estimates of 7.15 and 268.38 t ha^{-1}, respectively. The aboveground carbon biomass reported in the Asha-Guba forest (210 t C ha^{-1}) is higher than that in the Chilimo natural forest of Ethiopia (200 t C ha^{-1}) (Tesfaye et al. 2019), similarly, the belowground carbon biomass is higher than that that in the Muktar forest eastern Ethiopia (Wodajo et al. 2020).

Soil organic carbon (SOC) of the forests

Forests can store significant quantities of carbon in the biomass and the soil (Mukul et al. 2020). Soil depth, soil bulk density, and concentrations of SOC are the three major variables considered for the estimation of SOC. The mean SOC in the 0-10 cm, 10-20 cm and 20-30 cm soil depths was 24.09 ± 0.14 t C ha^{-1}, 22.77 ± 0.119 t C ha^{-1} and 22.49 ± 0.12 t C ha^{-1}, respectively. Thus, the highest SOC was stored in the upper soil surface of 0-10 cm depth, due to higher amount of organic matter accumulation in this layer. In this regard, similar studies conducted so far confirmed that SOC decreased with increasing depth in forest soils (Abere et al. 2017). The higher proportion of carbon stocks is stored in the organic layer (Wellbrock et al. 2017). Similarly, in this study, the highest percentage of carbon was stored in the form of soil organic carbon (61%) followed by the ABGL biomass carbon pool (30%). The results agree with other results reporting an important portion of total carbon stock was in the forest soils (Tolunay 2011). Hence, forest soil carbon management intervention is indispensable to safeguarding the leaching of soil organic carbon. Moreover, there is a need to adapt the carbon management approach to forest management (Tolunay 2011).

Carbon stock in dead organic matter (DOM) of the forests

Reliable estimates of the total forest carbon pool are lacking due to insufficient information on dead organic matter (Zhu et al. 2017). Here, we estimated the DOM in community forest of Ethiopia. Dead wood carbon accounts for standing and laying dead wood as well as dead stumps of logged trees. Carbon stocks generally ranged from 0.00-7.95 t ha^{-1}, with the highest mean dead wood carbon in Asha-Guba community forest (i.e., 1.04 ± 0.31 t ha^{-1}). While, the mean dead wood carbon stock in Beshilo plantation forest were 0.11 ± 0.06 t ha^{-1}, while there was no dead wood in Jemely natural forest. This might be due to the longer life span and lower timber quality of dominant tree species in Jemely natural forest. Regarding carbon stock in surface litter, the opposite was true, i.e. surface litter carbon is higher in natural forest than in plantation. The laboratory (field level) analysis of litter carbon provides a mean record of 0.12 ± 0.03 t ha^{-1} in Jemely natural forest. In terms of carbon accounting, the variation between natural and plantation forest was insignificant, but it has more meaning in the analysis of disturbance in the forest ecosystem (Figure 3).

Meanwhile, the amount of carbon harvested from the forest included the parameters of sound, coppiced and dead stump. Stumps height, diameter at the top of stumps and number of stumps were considered to compute the equivalent basal area at 1.3 m height of a given species. Accordingly, the regression equation developed from a sample height curve relationship (Murdiyarso et al. 2008) was considered for the estimation of missing tree DBH and height in the case of the stump. The result revealed that the highest value of HW carbon (i.e., 22.52 t ha^{-1}) was estimated from the Asha-Guba plantation and the list observation (i.e., 0) was from the Jemely natural forest. The mean HW carbon of 8.01 ± 0.81 t ha^{-1}, 0.57 ± 0.26 t ha^{-1}, and 1.47 ± 0.47 t ha^{-1}, respectively were estimated from Asha-Guba, Jemely, and Beshilo forest sites. This shows that the Asha-Guba plantation forest was at high risk of deforestation than the Beshilo and Jemely forests. This is due to selective harvesting of tree species (Zhu et al. 2017).

Total forest carbon stock (TCS) of the forests

The overall mean carbon stock density (t ha^{-1}) of the study area was computed from all major carbon pools and all forest sites, resulting in value of 113.71 ± 3.95 t ha^{-1}. The use of this value for total carbon stock estimation was misleading because the Analysis of Variance conducted showed a significant difference between and among carbon density in the forests at 95% CI. Thus, the total carbon stock of the study area was computed by summing up the product of carbon density per site with the respective areas in a hectare. Accordingly, TCS currently stored in Asha-Guba, Jemely, and Beshilo forests was 40,014.94 ± 8.29 tons; 11,861.2 ± 2.39 tons; and 5,736 ± 3.13 ton respectively. Therefore, the unknown true value of TCS currently estimated in community forests was within the interval of 57,598.33 to 57,625.95 tons.

The TCS density (t ha^{-1}) estimated for Jemely (91.24 t ha^{-1}) was 3 to 5 times lower compared to other natural forest such as 586.7 t ha^{-1} in Gerba Dima (Dibaba et al. 2019), 353.6 t ha^{-1} in Anbesa forest (Yohannes 2016) , and against the national average TCS density of natural high forest 128 t ha^{-1} (Yitebitu et al. 2010). On the other hand, the biomass carbon from Asha-Guba and Beshilo plantation forests was lower by 29 t ha^{-1} compared with the national average (147.6 t ha^{-1}) (Tadesse et al. 2020). Also, the total carbon biomass density of both plantation and natural forest (94.38 t ha^{-1}) was 50% of the tropical rain forest estimate of 200 t ha^{-1} (Eggelston et al. 2006).

Estimated the baseline emission of the community forests

The total forest area reduced from 530 ha (pre-deforestation) to 411 ha as a result of historic deforestation (Biadgligne 2021). The annual rate of deforestation in the period of 2010 to 2020 was 1.87% per year. However, after deforestation some amount of carbon stocks were deposited in the residual vegetation known as Anthropic Vegetation in Equilibrium (AVE). Thus, the Ex-ante post deforestation

class tCO_2e emission was computed by subtracting the default value of AVE which is 18 tCO_2e ha^{-1}. Therefore, through BAU scenario 76.96 ha or 18.72% of the current forest area (411ha) will be converted to non-forested area by 2030. Even, this figure will be escalated due to the aggregate effect of severe forest degradation in the area. Likewise, with the average net emission factor of 136 tCO2e ha^{-1}, by 2030 a total of 10466.8 tCO_2e emission expected in the post deforestation class. Unless immediate remedial measures be taken to curve this scenario, it is impossible to receive result-based payment. Under the Business-As-Usual scenario, the next 20 years would lead to the emission of 90 million tCO_2 from the forest sector (FDRE 2018). It was stated in the USAID (2011) the annual emission of GHGs in Ethiopia is 150 Mt CO_2 equivalents. In Ethiopia, the forest sector is the second largest source of national GHG emission (55 million tCO_2e) after agriculture (75 million tCO_2e). Projections indicate that mean annual temperature across the country will increase with a range of 1.4 to 2.9°C by the 2050s (Conway and Schipper 2011). Compared to the global annual emission of the same year, the emission from Ethiopia is less than 0.3%, yet it is among the top 40 countries (of 185) that are considered most vulnerable to climate change (USAID 2011). Halting deforestation and maintaining forests using forests and building green value (FAO 2022) is a good opportunity to better understand the existing forest condition.

In conclusion this study estimated carbon stock and emission in community forests of Eastern Amhara, Ethiopia. The carbon stock density and emission factor (tCO_2e) were computed using data generated from 57 systematically aligned nested quadrats. The empirical analysis revealed that, currently on average 113.71±3.95 t ha^{-1} (416.18 tCO_2e ha^{-1}) of carbon is sequestered and stored in the various forest carbon pools with a significant difference between and among sites. The highest proportion of carbon (61%) was stored in the soil pool followed by ABGL biomass (30%). However, the contribution of shrubs, herbaceous vegetation, surface litter and dead wood was insignificant, with no statistically significant difference between ABGL shrubs and DW carbon (P=0.05). This result calls an adaptive community forest management practice in the area. Harvesting forest products may results carbon leaching so that attention should be given on construction of soil conservation structure before harvesting. The TCS estimated at 95% CI was within the range of 56,001.12 to 59,224.96 tons or 204,964.1 to 216,763.4 tons of CO_2e carbon. The next main question in this study sought to estimate the baseline CO_2e emission factor of the study area. Emission Factor (tCO_2e ha^{-1}) in the pre-deforestation period, the amount of carbon estimated from HW (extracted through clear-cutting and selective logging) has been added to ABG biomass carbon which was 42.078 t ha^{-1}. The average net emission factor of 136 tCO_2e ha^{-1}, by 2030 a total of 10466.8 tCO_2e emissions are estimated. Setting reference data is vital for the implementation of carbon credit systems and to undertake performance evaluation in community forest management.

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Identification and characterization of traditional agroforestry practices and their socioeconomic roles in Dendi District, Central Ethiopia

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Abstract. *Humnessa T, Gebretsadik W, Negasa A. 2022. Identification and characterization of traditional agroforestry practices and their socioeconomic roles in Dendi District, Central Ethiopia. Asian J For 6: 83-89.* This study was conducted in the Dendi District of Central Ethiopia in three *kebele* (smallest administration units in Ethiopia) to identify and characterize the existing traditional agroforestry practices and their contribution to household livelihood. Informal surveys were conducted through key informant interviews and physical observations, while formal surveys were conducted using structured questionnaires. Home gardens, scattered trees on cropland, scattered woody species on grazing land, live fencing, and rarely woodlots were traditional agroforestry practices identified in the area. Home gardens were the prevailing traditional agroforestry practices in the study area. Fifty-seven (57) perennial woody species and twenty-two (22) annual crops (including vegetables and crops) in the home garden, twelve (12) species of scattered trees on cropland, twenty-eight (28) woody species on grazing land, twenty-four (24) woody species on the live fence, and two (2) woody species on woodlots were planted and managed in the study area for several purposes. Except for woodlots, most woody species in traditional agroforestry were grouped under the Fabaceae family. Furthermore, most associated annual crops in home garden agroforestry were categorized under the Solanaceae family. Different tree management practices, such as branch pruning, coppicing, pollarding, and thinning, were undertaken by agroforestry practitioners to reduce negative interaction among components and maximize the overall products of the system.

Keywords: Dendi, home garden, scattered trees, woodlot, woody species

INTRODUCTION

Today's world, including Ethiopia, faces many challenges related to declining vegetation cover, land degradation, unsustainable farming practices, rising hunger, and poverty. Agroforestry has a high potential to provide both sustainable products and environmental services (Sharma et al. 2007; Nyaruai et al. 2018). It is a farming system in which trees or shrubs are grown in association with crops, pastures, or livestock. The positive interaction between trees and other components increases land users' social, economic, and environmental benefits (Leakey 1996). In Ethiopia, traditional agroforestry, a household strategy of land use system to provide food, fuel-wood, timber and fodder, protection, and other values as a model for sustainable forestry and agricultural practices, has been practiced for a long period. Traditional agroforestry practice may include home gardens, defined as an agroforestry system in which woody plant species and crops/vegetables are closely integrated around farmers' homesteads and managed mainly by family labor to stabilize their food security (Nair 1993; Kebebew et al. 2018). Multipurpose woody species on croplands, which is considerately incorporating woody plant species in annual croplands for various purposes such as fulfilling farmers' need for timber products. Also on conserving native woody species and conserving biological diversity (Giday et al. 2019). Furthermore, it is useful for improving the production of annual food crops and non-food goods (Gebrewahid and Abrehe 2019). Trees in live fences are multipurpose woody species planted around a house, cropland, and garden for protection. Trees in multipurpose woodlots are small patches of land planted with trees on individual farms or communal lands for various purposes. Moreover, scattered trees on grazing lands are referred to as the management and conservation of scattered trees and other woody species on grazing lands.

Agroforestry, where trees are integrated with crops and livestock, is a promising land management system that can address many challenges farmers encounter (Lundgren and Raintree 1982). For example, Agroforestry has the potential to mitigate climate change and adapt resource-poor smallholder farms to extreme and variable weather. Furthermore, it could increase tree-related essential ecosystem services while increasing farm productivity without reliance on large amounts of external inputs such as inorganic fertilizers and chemicals for pest management (Agroforestry Network 2018).

The first principle of agroforestry is that plants work and grow best in cooperation. This notion is against the conventional agricultural view. In the conventional agricultural view, plants brought together on a parcel of land compete for a limited environmental resource, resulting in yield loss. On the contrary, agroforestry examined how plants cooperate rather than how they compete. Each plant is considered to have a unique role in the ecosystem, and agroforestry tries to put plants in a mutually beneficial relationship: companion planting. Companion plants may provide yield at one time or render their ecosystem service (Shade, insect pollination, etc.) at

other times. Agroforestry is an early farming system characterized by managing complex natural systems rather than destroying local ecosystems to grow crops (Dara Casey, 2022)

Even though traditional agroforestry systems have contributed immensely to households' food security improvement and environmental protection in Ethiopia, less attention is given to improving the system. Furthermore, it is important to identify and characterize the existing traditional agroforestry practices in the area and the species compositions to modify farmers' knowledge of different traditional agroforestry practices. In agroforestry research, practices are often applied after diagnosis and design, participatory research, or characterization studies, depending on an area's social, economic, and environmental problems (Leakey 1996). Thus, we conducted the current study with the overall objective of identifying and characterizing the existing traditional agroforestry practices and their contribution to household livelihood, which will be used as baseline data for further development and research activities.

MATERIALS AND METHODS

Description of the study area

Dendi is one of the 19 districts/ *woredas* (administration units higher than *kebele*s) of the West Shoa zone of the Oromia regional state, Ethiopia, within 8°7'19"-9°15'1"N and 37°9'15"-38°3'41"E with an altitudinal range from 2,000-3,200 meter above sea level. The district's capital town, Ginchi, is located 75 km West of Addis Ababa. The district has a total area of 109,555 ha. The district is bordered in the South by Bacho and Dawo Districts, in the East by Ejere District, in the West by the Ambo district, and in the North Jeldu district (Figure 1).

Survey procedures

The specific study sites and prioritization of agroforestry practices were identified through discussions with different district stakeholders in the study area (administrations, development agents, and relevant experts). Based on these discussions, the purposive sampling method, a robust non-random sampling method to pick out intensive agroforestry practitioners and knowledgeable key informants in the community, was employed to get basic information from the selected *kebele*s (smallest administration units in Ethiopia).

Purposive sampling is a more robust technique than random sampling because random community members may not be known as expert informants (Tongco 2007). Thus, three *kebele*s (Bajiro, Boda Boseqa, and Gare Arera) were selected for this study for key informant interviews. Ten households were selected from each *kebele*s as a sample and assigned to be interviewed. The primary information was collected through formally structured questionnaires, key informant interviews, and physical observation. In addition, secondary information was collected from the district agricultural office, *kebele*s Farmers' Training Centre (FTC), and other relevant stakeholders.

Finally, all selected kebeles groups comprised ten key informants representing elders, youth group, male-headed and female-headed. The selection was based on their long residence in the study area, good knowledge of traditional agroforestry practices, and ability to express the functioning and historical development of traditional agroforestry practices in the area. The nomenclature of plant specimens collected from the home garden follows Bekele-Tesemma and Tengnäs (2007). Collected data were subjected to SPSS 20 statistical software and Microsoft Excel 2010 for analysis.

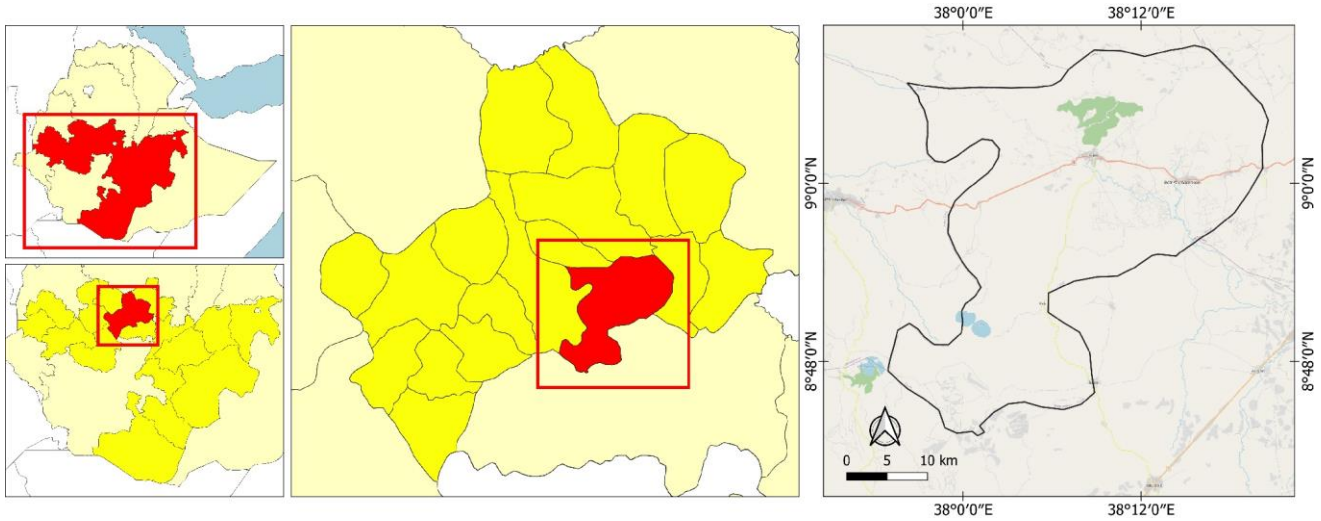

Figure 1. Map of the study area in Dendi District, Oromia State, Ethiopia

RESULTS AND DISCUSSION

Trends of vegetation cover

Most respondents from the interviewed household heads at Bajiro (90%) and Boda Boseqa (80%) replied that the vegetation cover of the area is decreasing from time to time. In comparison, at Gare Arera, the majority of respondents (above 70%) replied that it is increasing; the reason for increasing of vegetation coverage at Gare Arera *kebele* is mainly attributed to the participatory forest management activity of the Chillimo natural forest, where the respondents were located (Figure 2).

Landholding and classification of land use

Survey results showed that relatively larger land holdings that ranged from 1.00 ha to 3.75 ha were observed at Boda Boseqa *kebele*s. Gare Arera had the least land holding size comparatively, averaging about 1.23 ha. The dominant land uses identified in the study area include cropland, grazing land, and home garden agroforestry. Traditional agroforestry was frequently observed in land use at all interviewed households. At Bajiro and Boda Boseqa, significantly larger areas are allocated for cropland, while at Gare Arera, the coverage for home garden agroforestry practices was significantly higher than other land uses (Figure 3).

Traditional home garden agroforestry

The survey results showed that home gardens commonly practiced traditional agroforestry activities in the study area. Multipurpose woody plant species were incorporated and managed with various associated crops, vegetables, and spices in the backyard of households. As a result, fifty-seven woody species representing thirty-seven families were recorded in traditional home garden agroforestry practices (Table 1). Of thirty-four woody species managed in the home garden, 74% were native, while the rest, 26%, were exotic species. At the family level, Fabaceae was the most dominant family, represented by nine woody species, followed by Rosaceae, a family of five woody species. Similarly, twenty-two species of various associated crops and vegetables representing fifteen families were recorded in the traditional home garden agroforestry practices (Table 2).

For associated crops and vegetables, Solanaceae was the most dominant family, represented by four woody species, and Poaceae, represented by three woody species. The major woody species recorded were *Vernonia amygdalina* Delile, *Croton macrostachyus* Hochst, *Buddleja polystachya* Fresen, *Catha edulis* (Vahl) Endl., *Dombeya torrida* J.F.Gmel., *Cordia africana* Lam., and *Olea africana* Mill. The associated crops and more frequently recorded species were *Ensete ventricosum* Welw, *Allium cepa* L., *Allium sativum* L., *Solanum tuberosum* L., and *Brassica carinata* A., commonly practiced as understory crops and vegetables. These findings are similar to those reported by Yusuf and Solomon (2019) on home garden agroforestry (Figure 4).

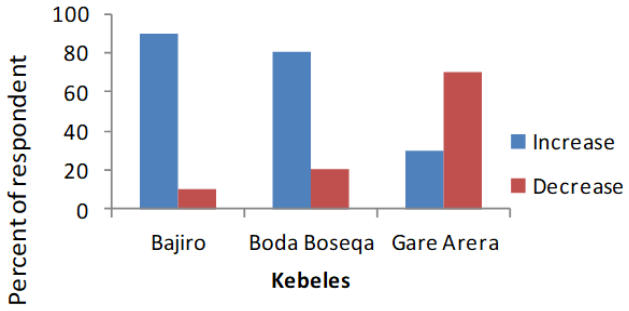

Figure 2. Comparison of responses on trends of vegetation covers across sampled *kebeles*

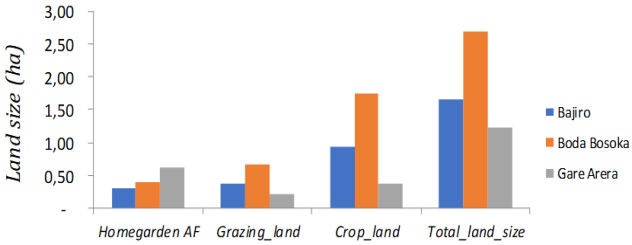

Figure 3. Landholding size and characterization of land use

Figure 4. Home garden agroforestry of the study area

Table1. Woody species managed in home gardens

Species	Family	Freq.	% of Freq.
Acacia abyssinica Hochst.	Fabaceae	12.00	2.39
Acacia decurrens Willd.	Fabaceae	1.00	0.20
Acacia saligna Labill.	Fabaceae	14.00	2.79
Albizia gummifera J.F.Gmel.	Fabaceae	8.00	1.59
Aleurites moluccanus Willd.	Euphorbiaceae	16.00	3.19
Arundinaria alpina K.Schum.	Poaceae	1.00	0.20
Balanites aegyptiacus L.	Balanitaceae	1.00	0.20
Buddleja polystachya Fresen.	Scrophulariaceae	27.00	5.38
Calpurnia aurea Benth.	Fabaceae	1.00	0.20
Carissa edulis Forssk.	Apocynaceae	2.00	0.40
Casuarina equisetifolia L.	Casuarinaceae	2.00	0.40
Catha edulis (Vahl) Endl.	Celastraceae	24.00	4.78
Celtis africana Burm.f.	Cannabaceae	1.00	0.20
Chamaecytisus palmensis H. Christ	Fabaceae	21.00	4.18
Citrus aurantium L	Rutaceae	14.00	2.79
Citrus sinensis L.	Rutaceae	1.00	0.20
Coffee arabica L.	Rubiaceae	15.00	2.99
Cordia africana Lam.	Boraginaceae	19.00	3.78
Croton macrostachyus Hochst.	Euphorbiaceae	26.00	5.18
Cupressus lusitanica Mill.	Cupressaceae	5.00	1.00
Dombeya torrida J.F.Gmel.	Sterculiaceae	20.00	3.98
Dovyalis abyssinica A.Rich.	Flacourtiaceae	6.00	1.20
Ekebergia capensis Sparrm.	Meliacieae	6.00	1.20
Erythrina brucei Schweinf.	Fabaceae	13.00	2.59
Eucalyptus globulus Labill.	Myrtaceae	8.00	1.59
Euclea schimperi Hiern	Ebenaceae	1.00	0.20
Ficus sur Forssk.	Moraceae	2.00	0.40
Grevillea robusta A. Cunn.	Proteaceae	4.00	0.80
Hagenia abyssinica J.F.Gmel.	Rosaceae	1.00	0.20
Hypericum revolutum Vahl	Hypericaceae	17.00	3.39
Juniperus procera Hochst.	Cupressaceae	4.00	0.80
Justicia schimperi Hochst.	Acanthaceae	1.00	0.20
Lippia javanica Burm.f.	Verbenaceae	18.00	3.59
Maesa lanceolate Forssk.	Myrsinaceae	9.00	1.79
Magnifera indica L	Anacardiaceae	2.00	0.40
Malus domestica Borkh	Rosaceae	23.00	4.58
Maytenus arbutifolia Hochst.	Celastraceae	3.00	0.60
Millettia ferruginea Hochst.	Fabaceae	7.00	1.39
Myrica salicifolia Hochst.	Myricaceae	1.00	0.20
Myrsine africana L	Primulaceae	1.00	0.20
Olea africana Mill.	Oleaceae	18.00	3.59
Osyris compressa (P.J.Bergius).	Santalaceae	1.00	0.20
Persea americana Mill.	Lauraceae	7.00	1.39
Phytolacca dodecandra Hoffm.	Phytolaccaceae	1.00	0.20
Pittosporum viridiflorum Sims.	Pittosporaceae	3.00	0.60
Podocarpus falcatus (Thunb)	Podocarpaceae	4.00	0.80
Prunus africana (Hook.f.)	Rosaceae	11.00	2.19
Prunus domestica L	Rosaceae	9.00	1.79
Psidium guajava L	Myrtaceae	1.00	0.20
Rhamnus prinoides L'Hér.	Rhamnaceae	20.00	3.98
Rhamnus staddo R.Br.	Rhamnaceae	3.00	0.60
Rhus vulgaris Meikle	Anacardiaceae	2.00	0.40
Rosa abyssinica R.Br.	Rosaceae	11.00	2.19
Salix subserrata Willd.	Salicaceae	3.00	0.60
Sesbania sesban (L.)	Fabaceae	16.00	3.19
Vernonia amygdalina Delile	Asteraceae	33.00	6.57
Vernonia auriculiolia Hiern	Asteraceae	1.00	0.20

Table 2. Crops and vegetables in the traditional home gardens

Scientific name	Family	Freq.	Percent (%)
Vicia faba L.	Fabaceae	10	3.08
Allium cepa L.	Amaryllidaceae	8	2.46
Ocimum basilicum L.	Lamiaceae	16	4.92
Zea mays L.	Poaceae	10	3.08
Ruta chalepensis L.	Rutaceae	18	5.54
Cucurbita pepo L.	Cucurbitaceae	14	4.31
Solanum tuberosum L.	Solanaceae	26	8.00
Beta vulgaris L.	Amaranthaceae	18	5.54
Daucus carota L.	Apiaceae	4	1.23
Cymbopogon citratus (DC.)	Poaceae	10	3.08
Musa acuminate Colla.	Musaceae	6	1.85
Capsicum annuum L.	Solanaceae	1	0.31
Allium sativum L.	Alliaceae	27	8.31
Allium cepa L.	Alliaceae	29	8.92
Brassica carinata A.	Cabombaceae	26	8.00
Brassica oleracea L.	Brassicaceae	22	6.77
Lactuca sativa L.	Asteraceae	11	3.38
Rosmarinus officinalis L.	Lamiaceae	5	1.54
Saccharum officinarum L.	Poaceae	13	4.00
Nicotiana tabacum L.	Solanaceae	1	0.31
Lycopersicon esculentum Mill.	Solanaceae	20	6.15
Ensete ventricosum Welw.	Musaceae	30	9.23

Scattered multipurpose woody species on cropland

Trees planted in this traditional agroforestry practice were woody species preferred by farmers and rarely naturally grown trees and shrubs maintained in scattered densities. Survey results showed the presence of 12 woody species of trees and shrubs representing ten families at the study site (Table 3). Of twelve woody plant species planted and managed on croplands, 82% were native. At the family level, *Fabaceae* was the most dominant family, represented by three woody species, while one species represented the rest families. The *B. polystachya*, *C. macrostachyas*, *V. amygdalina*, *Dovyalis abyssinica* A.Rich., and *Acacia abyssinica* Hochst. were the most frequently observed multipurpose woody species on cropland in the study area.

In contrast, *Juniperus procera* Hochst., *Podocarpus falcatus* (Thunb), and *Erythrina brucei* Schweinf. were rarely observed. Results indicated that most households prefer indigenous tree species to manage on their cropland for soil fertility improvement, timber production, shade for their livestock, and rarely to hang traditional beehives. This finding is in line with other studies elsewhere in Ethiopia on scattered tree species on farmlands (Alebachew 2012; Yusuf and Solomon 2019).

Scattered woody species on grazing lands

We commonly practiced deliberate protection and management of naturally grown trees on grazing land and planting selected multipurpose woody species in all study areas. However, we rarely practiced planting different multipurpose woody species in the area. Survey results showed that 28 woody species representing 20 families were planted and managed on grazing land (Table 4). Of twenty-eight woody species managed and planted on grazing lands, 82% were native, while the rest 18 woody

species were exotic. At the family level, the most dominant family was *Fabaceae*, represented by four woody species. In addition, two woody species represented five families, Casuarinaceae, Cupressaceae, Euphorbiaceae, Primulaceae, and Rosaceae. Furthermore, only one species represented the remaining 14 families. Of identified woody species, *J. procera*, *P. falcatus*, *A. abyssinica*, *Eucalyptus globulus* Labill., and *C. macrostachyas* were the most frequent woody species managed on grazing land in the study areas. At the same time, *Euclea schimperi* Hiern, *Carissa edulis* Forssk. and *Salix subserrata* Willd. were the least occurring species in the area.

Woody species used for live fence/boundary planting:

The study indicated that different woody species were planted as live fences around a house, cropland, and between the boundaries of farmlands. Mainly the purposes of the live fence/boundary planting are protection and shelter against animals and wind, shade, and rarely some leguminous shrubs between the boundaries of croplands are planted for fodder, soil fertility, and soil and water conservation. Besides its deliberate benefits, woody species planted for fencing can provide fuel-wood, food, and fodder and serve as beautification. Twenty-four woody species representing 16 families were planted for living fences in the study area (Table 5). At the family level, the most dominant family was Fabaceae, represented by three woody species. In comparison, the remaining 15 families were represented by one species. The *D. abyssinica*, *Calpurnia aurea* Benth., *E. globulus*, *Rosa abyssinica* R.Br. ex. Lindl, and *Cupressus lusitanica* Mill. were priority species by farmers for live fence planting.

Multipurpose woodlots

In the study area, plantations (in-situ conservation) of woody species in the form of woodlots to achieve several objectives (timber, fodder, soil protection, and soil reclamation) were practiced. A survey indicated that *E. globulus* (86%) was a commonly planted species for woodlots, while naturally grown *J. procera* (14%) was managed as woodlots for various purposes.

Table 1. Woody species managed on farmland

Scientific name	Family name	Freq.	% of freq.
Acacia saligna Labill.	Fabaceae	1	1.02
Buddleja polystachya Fresen.	Scrophulariaceae	18	18.37
Croton macrostachyus Hochst.	Euphorbiaceae	16	16.33
Podocarpus falcatus (Thunb)	Podocarpaceae	2	2.04
Dombeya torrida J.F.Gmel.	Sterculiaceae	13	13.27
Vernonia amygdalina Delile	Asteraceae	15	15.31
Olea africana Mill.	Oleaceae	10	10.20
Juniperus procera Hochst	Cupresaceae	2	2.04
Acacia abyssinica Hochst.	Mimosaceae	12	12.24
Sesbania sesban (L.)	Fabaceae	3	3.06
Ekebergia capensis Sparrm.	Casuarinaceae	4	4.08
Erythrina brucei Schweinf.	Fabaceae	2	2.04

Table 4. Woody species, managed and planted on grazing lands

Scientific name	Family name	Freq.	% of freq.
Malus domestica Borkh	Primulaceae	2	1.35
Acacia decurrens Willd	Fabaceae	4	2.70
Acacia saligna Labill.	Fabaceae	2	1.35
Euphorbia abyssinica J.F.Gmel.	Euphorbiaceae	4	2.70
Carissa edulis Forssk.	Apocynaceae	1	0.68
Salix subserrata Willd.	Salicaceae	1	0.68
Eucalyptus globulus Labill.	Myrtaceae	12	8.11
Croton macrostachyus Hochst.	Euphorbiaceae	8	5.41
Podocarpus falcatus (Thunb)	Podocarpaceae	16	10.81
Vernonia amygdalina Delile	Asteraceae	4	2.70
Olea africana Mill.	Oleaceae	7	4.73
Juniperus procera Hochst.	Cupressaceae	23	15.54
Cupressus lusitanica Mill.	Cupressaceae	3	2.03
Grevillea robusta A. Cunn	Proteaceae	4	2.70
Ficus sur Forssk.	Moraceae	2	1.35
Hagenia abyssinica J.F.Gmel.	Casuarinaceae	3	2.03
Prunus africana (Hook.f.)	Rosaceae	3	2.03
Rosa abyssinica R.Br. ex. Lindl.	Rosaceae	4	2.70
Maytenus arbutifolia Hochst.	Celastraceae	2	1.35
Acacia abyssinica Hochst.	Mimosaceae	14	9.46
Euclea schimperi Hiern	Ebenaceae	1	0.68
Myrsine africana L	Primulaceae	4	2.70
Rhamnus staddo R.Br.	Rhamnaceae	2	1.35
Ekebergia capensis Sparrm.	Casuarinaceae	4	2.70
Pittosporum viridiflorum Sims.	Pittosporaceae	3	2.03
Millettia ferruginea Hochst.	Fabaceae	7	4.73
Osyris compressa Decn	Santalaceae	2	1.35
Erythrina brucei Schweinf.	Fabaceae	6	4.05

Table 2. Woody species for live fence/boundary planting

Scientific name	Family name	Freq.	% of freq.
Acacia decurrens Willd	Fabaceae	9	4.71
Buddleja polystachya Fresen.	Scrophulariaceae	2	1.05
Eucalyptus globulus Labill.	Myrtaceae	18	9.42
Croton macrostachyus Hochst.	Euphorbiaceae	4	2.09
Podocarpus falcatus (Thunb)	Podocarpaceae	2	1.05
Calpurnia aurea Benth	Fabaceae	22	11.52
Vernonia auriculiolia Hiern	Asteraceae	11	5.76
Dombeya torrida J.F.Gmel.	Sterculiaceae	6	3.14
Vernonia amygdalina Delile	Asteraceae	8	4.19
Olea africana Mill.	Oleaceae	2	1.05
Juniperus procera Hochst.	Cupressaceae	8	4.19
Cupressus lusitanica Mill.	Cupressaceae	14	7.33
Rubus steudneri Schweinf.	Rosaceae	2	1.05
Grevillea robusta A. Cunn	Proteaceae	10	5.24
Rosa abyssinica R.Br.	Rosaceae	15	7.85
Maytenus arbutifolia Hochst.	Celastraceae	1	0.52
Dovyalis abyssinica A.Rich.	Salicaceae	22	11.52
Rhamnus staddo R.Br.	Rhamnaceae	1	0.52
Sesbania sesban (L.)	Fabaceae	9	4.71
Casuarina equisetifolia L.	Casuarinaceae	14	7.33
Ekebergia capensis Sparrm.	Casuarinaceae	2	1.05
Chamaecytisus palmensis H. Christ	Fabaceae	5	2.62
Osyris compressa (P.J.Bergius).	Santalaceae	1	0.52
Erythrina brucei Schweinf.	Fabaceae	3	1.57

Purposes of planting woody species on traditional Agroforestry practices

The survey results indicated that in the study area, different woody species are planted in traditional Agroforestry practices (home gardens, farm lands, grazing lands, live fence/boundary planting, and woodlots) for various purposes. We found from respondents' replies that the woody species are mostly planted and managed for construction, fuel wood and charcoal, income generation, shade and shelter, soil fertility, and medicinal values (Figure 5). Of woody species planted and managed for traditional agroforestry practices, the respondents planted most for fuel-wood, shade, construction, soil fertility, and income generation. This finding is consistent with the study by Gebretsadik et al. (2018) and Tefera et al. (2019).

Management practices for woody species in traditional agroforestry practices

This study rendered different management practices to woody species on traditional agroforestry practices in the areas, including pollarding (55%) and branch pruning applied to (45%) of the scattered trees on croplands. Branch pruning (51%), coppicing (7%), pollarding (30%), and thinning (30%) of the woody species on grazing land were implemented. Therefore, (61%) of branch pruning, (3%) of pollarding, and (36%) of thinning were applied for live fence/boundary planting. Similarly, branch pruning (24%) and coppicing (76%) were implemented for woodlots, while branch pruning (49%), thinning (6%), and pollarding (46%) were implemented in the home garden.

The objective of applying the mentioned management practices is to reduce negative interactions between components and maximize the system's overall products/values per land management unit. For example, branch pruning and pollarding in cropland, home gardens, and rangeland facilitate light interception to the understory. That would reduce competition for light among those multipurpose woody species and associated crops. Additionally, timber and fuel wood products were obtained during these management practices.

Contribution of traditional agroforestry practices to household livelihood

Results from the survey indicated that traditional agroforestry practice provides many benefits for local communities to improve their livelihood. The respondents said that their major benefits from a home garden were economic, ecological, and social. They mainly generated incomes from products of traditional home garden agroforestry practices (fruits, associated vegetables, and crops, and other practices also generated income from selling timber and other related products). Additionally, there are fruits, understory vegetables, and crops cultivated in home garden agroforestry were used for household consumption (Figure 6).

In the study area, livestock production is one of the income-generation activities practiced by most households. In addition to grazing lands, livestock feeds were mainly obtained from by-products of different vegetables and crops cultivated in home gardens. Additionally, leaves and flowers of different woody species planted for live fence/boundary planting and on farmland and grazing land were highly used as a source of forage for livestock. For instance, in Boda *kebeles*, the respondents said that, during a dry season, they feed their livestock with the leaves and other parts of 'enset' (*E. ventricosum*) used to overcome the shortage of animal feed caused by drought. Besides its benefits as a source of fodder, woody species planted in different agroforestry practices can also serve as shade for livestock. This study finding is in line with the study conducted by Amenu (2017).

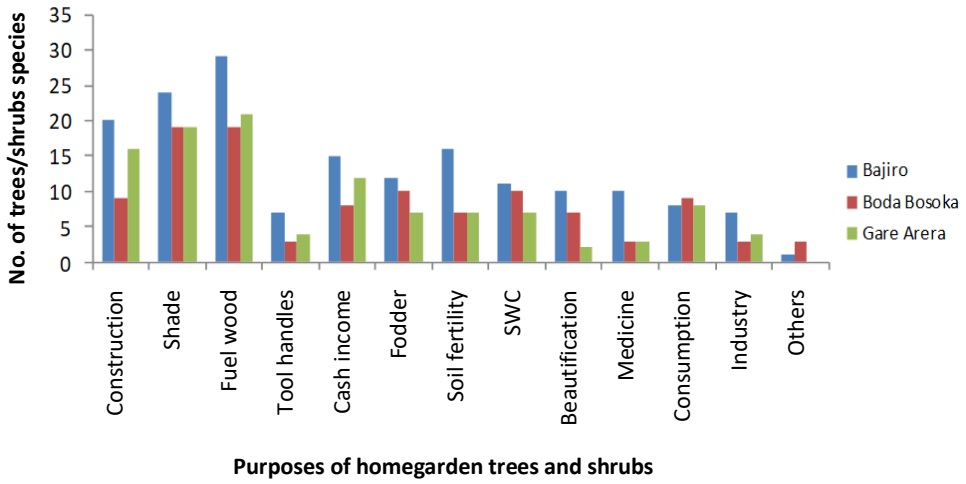

Figure 5. Purposes of planting trees and shrubs around the homestead

Figure 6. Various products obtained from traditional home garden agroforestry

In conclusion, most of the vegetation observed in the area were woody species managed in different traditional agroforestry practices. Such as home gardens, selected multipurpose tree species on croplands, woody species on grazing land, woodlots, and live fencing. Different multipurpose woody species were managed and conserved in all identified land use types for household consumption, timber production, income generation, fodder, soil fertility improvement, and protection. The plantation of *E. globulus* and infrequent natural regenerations of *J. procera* were managed as monoculture woodland by a few farmers in the study areas. Different management practices were observed, including branch pruning, coppicing, pollarding, and thinning of woody species of traditional agroforestry practices to reduce negative interactions among components and maximize overall function. Diversified agroforestry products from different traditional agroforestry practices provided countless benefits for local communities in improving their livelihood. A future study is suggested to promote the most preferred woody species from identified agroforestry practices in the area.

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Vertical distribution of soil properties and soil organic carbon in community managed forest of Siwalik Hill, Nepal

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Abstract. *Lamichhane U, Ghimire P. 2022. Vertical distribution of soil properties and soil organic carbon in community managed forest of Siwalik Hill, Nepal. Asian J For 6: 91-96.* Nepal's Community Forestry (CF) approach is globally recognized as an innovative and successful approach to forest resource management. *Shorea robusta* Gaertn. is the dominant tree species of Nepal's forest which covers 19.28% of the total stem volume of the country's forest area. Soil represents a significant terrestrial Carbon (C) pool and can play a significant role in mitigating global warming. Therefore, analyzing soil physicochemical properties and Soil Organic Carbon (SOC) stock is essential because they are key parameters for evaluating land use management systems. The present study was conducted in the Durga Mai Community Forest (DMCF) of Makawanpur District, Nepal, to assess the vertical distribution of soil physicochemical properties and SOC stock. Soil samples within a 1 m profile in five depth layers (0-20 cm, 21-40 cm, 41-60 cm, 61-80cm, and 81-100 cm) were collected and analyzed for Bulk Density (BD), soil texture, soil pH, soil carbon content, Total Nitrogen (TN), Available Phosphorous (AP), Available Potassium (AK) and SOC stock. Sandy loam was the dominant soil textural class reported throughout the study area. Average BD, soil pH, TN, AP, and AK in the *S. robusta* forest's soil in 1 m soil profile depth were found to be 1.16 ±0.07 $gmcm^{-3}$, 5.78 ±0.62, 0.14 ±0.04 %, 5.94 ±1.04 $kgha^{-1}$, and 104.20 ±19.66 $kgha^{-1}$, respectively. The results estimated 107.57 ±3.06 tha^{-1} of SOC stock in 1 m soil profile, with 0.93 ±0.21% average SOC content. Further, average TN, AP, and AK were found to be decreased with an increase in soil profile depths. Similarly, soil profile depths significantly affected SOC stock and soil properties like BD, soil pH, TN, AP, and AK.

Keywords: Community forest, soil organic carbon, soil profile, soil properties

INTRODUCTION

Carbon (C) sequestration through forest soil has been reported to be a cost-effective means for mitigating global climate change. Soil can store three times more C than the amount in the atmosphere and 3.8 times more than in the biotic pool (Brown et al. 1996; FAO 2001; Lal 2004). Environmental degradation due to continuing land use and land cover changes is a major worldwide issue that has attracted the attention of global soil science studies (Ayoubi et al. 2011). The sustainability and functions of soil depend on dynamic symmetry among its physicochemical and biological properties, and the types and patterns of land constantly influence these uses (Shrestha et al. 2004; Ghimire et al. 2018;). Soil properties and soil C are often influenced by land use practices and have been reported to differ with the change in land use systems. In addition, forested land uses can largely influence the quality of the soil, which could be essentially linked to the sustainable functioning and production of forests and agroecosystems (Kotowska et al. 2015; Manpoong and Tripathi 2019). Studies have reported a significant decline in soil properties and soil C due to forest conversion to plantations (van Straaten et al. 2015; Guillaume et al. 2016). Those have raised serious concerns regarding the sustainability of such land use types in the tropics, particularly in Nepal (Lal 2010).

Soil C and soil properties are important factors in the global biogeochemical cycle of the terrestrial ecosystem and are vital for enhancing plant productivity, reducing land degradation, and mitigating global warming (Lal 2004; Ghimire et al. 2019; Yunanto et al. 2022). Additionally, they are the focus of a study on the global C balance and climate change. Soil C and soil properties have strong spatial variability (Zhao et al. 2000), and various factors such as forest types, land use types, and topography can influence soil C and soil properties at various scales (Twongyirwe et al. 2013; Fusaro et al. 2019; Ngaba et al. 2020). For example, Sal (*Shorea robusta* Gaertn.) is the most dominant tree species in the Terai and Chure ecological region of Nepal (Jackson 1994; DFRS 2016). This species shares the highest tree stem volume (i.e.31.76 m^3ha^{-1}), which is 19.28% of the tree stem volume of the country (DFRS 2016). The total C stock in Nepal's forests has been estimated as 1054.57 million tonnes (176.96 tha^{-1}), out of which forest soils constitute 37.80% (DFRS 2016). Therefore, forest land is one of the most important elements that regulate the SOC and soil properties build up because SOC and soil properties are greatly influenced by vegetation through the organic matter intake (Shi et al. 2015).

Forest ecosystems are the world's largest terrestrial C sinks, and their significance for the global C cycle and climate regulation cannot be ignored (Brown and Pearce 1994; Lal 2005). Community Forestry has been regarded as the highest priority of Nepal's forestry sector and is widely

acclaimed as a successful forest management approach. About 40% of the national forest in Nepal is under Community Forestry, where more than 3 million households are beneficiary users (DoF 2017; Ghimire and Lamichhane 2020). Recently, the opportunity for management of forests for enhancement of biomass and soil carbon sequestration and as a sink of greenhouse gases (GHGs) has emerged as a potential benefit for local communities participating in carbon trading under REDD+ agreements (Shrestha et al. 2013; Pandey et al. 2016). Furthermore, vertical patterns of SOC and soil properties can be used as an input or an independent validation for biogeochemical models, which can help understand how terrestrial ecosystems respond to climate change (Eswaran et al. 1993; Kern 1994; Mi et al. 2008). Previous research mainly concentrated on the topsoil C stock; however, the dynamics of C in deeper soil layers and the underlying mechanisms that govern vertical distributions of SOC and soil properties are still poorly understood (Jobbagy and Jackson 2000; Dahal and Kafle 2013). Only recently has the study of SOC in subsurface profiles attracted significant scientific attention due to the realization that subsoil carbon plays a significant role in the overall C storage within a soil profile (Batjes 1996). In Nepal, very few studies cover the vertical distribution of soil properties and SOC in forest ecosystems. Therefore, this study addresses this issue by addressing questions such as "What are the overall vertical patterns of SOC in *S. robusta* forest?" How much SOC is stored by the biosphere in the deep soil profile layers, and what impact do soil characteristics have on the soil C pool?

MATERIALS AND METHODS

Study area

The study was conducted in the Durga Mai Community Forest of Bakaiya Rural Municipality of Makawanpur District, Nepal (27° 32′ N, 85° 21′ E) (Figure 1). The forest covers 496.85 ha of the area. It consists mainly of natural *S. robusta* vegetation and other associated species such as *Terminalia tomentosa, T. bellerica, Lagerstroemia parviflora, Dalbergia sissoo, Acacia catechu,* and *Michelia champaca.* The study area is characterized by a tropical climate with an average temperature of 16 to 30 degrees Celsius and rainfall of 220 mm. The forest area represents sandstones, claystone, and conglomerates with quartz, feldspar, and opaque minerals of the lower and middle Chure range (DMCFUG 2017).

Soil sampling

Due to homogenous topography and forest cover density, soil samples were collected from 13 plots within the *S. robusta* forest following the simple random sampling technique. A W-type sample frame was used to represent all possible locations (Figure 1). Bulk samples were collected from a soil pit of 30 cm diameter by a cylindrical core sampler (5.5 cm diameter and 20cm length) for each incremental depth. The depth increment was 20 cm for the upper to lower soil profile (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm) down to 1 m soil profile. The fresh soil collected from each depth was kept in polythene bags and transported to the laboratory for further analysis. The selection of a 1 m soil profile was based on the literature that soil C studies usually consider a fixed soil depth, typically 1 m. In addition, global soil surveys based on vegetation units (Post et al. 1982) and soil taxonomic units indicate that the soil stores; 1500-1600 Pg of C in this first meter (Eswaran et al. 1993; Batjes 1996). Further, samples were sieved through a 2 mm mesh sieve to differentiate roots, stones, and debris, if any, and made ready for soil physicochemical analyses.

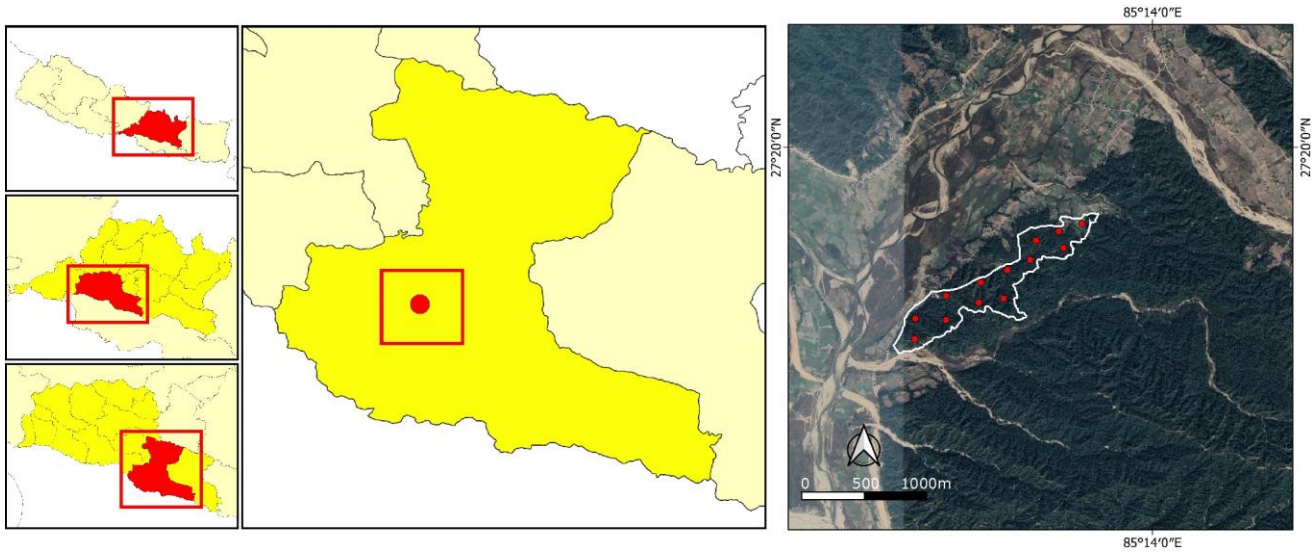

Figure 1. Map representing the study area n the Durga Mai Community Forest of Bakaiya Rural Municipality, Makawanpur District, Nepal

Analysis of SOC and soil properties

The core sampling method was used to determine soil bulk density (Blake and Hartge 1986). Then, soil texture was determined by the Bouyoucos hydrometer method (Bouyoucos 1962). Next, the textural classification, according to the United States Department of Agriculture (USDA), was followed to give the textural class of soil. Further, soil pH was measured by a digital pH meter (McLean 1982), total nitrogen (TN) by the Kjeldahl method (Bremner and Mulvaney 1982), available phosphorus (AP) by Olsen's and Somers method (Olsen and Sommers 1982), available potassium (AK) by flame photometer method (Thomas 1982) and SOC content by the colorimetric method (Anderson and Ingram 1993). Then, the total SOC stock was estimated by using the following formula recommended by Chhabra et al. (2003):

SOC (tha^{-1}) = Organic carbon content % x soil bulk density ($gm\ cm^{-3}$) × thickness of soil horizon (cm)

The one-way analysis of variance (ANOVA) was used to test the effects of different soil profile layers on soil physicochemical properties (such as bulk density, SOC content, soil pH, TN, AP, and AK), and SOC stock at a 5% level of significance. Further, the Pearson correlation test was applied to find the relationship between the studied variables.

RESULTS AND DISCUSSION

Soil physical properties

Sandy loam was the dominant soil textural class reported throughout the study area. However, the silt loam textural class was also found in the sub-soil layer. The overall mean of the sand, silt, and clay fraction was found to be 54.40± 5.07%, 30.14± 5.33%, and 15.46± 3.01% in *S. robusta* forest (Table 1). Similarly, the average BD of the *S. robusta* forest soil in 1 m soil profile depth was found to be 1.16 $gmcm^{-3}$ which ranged from 1.03 ± 0.09 $gmcm^{-3}$ (0-20 cm depth) to 1.29 ± 0.07 $gmcm^{-3}$ (80-100 cm depth) (Table 1). BD increased with increasing depths throughout the 1 m soil profile.

ANOVA test showed a significant difference of soil BD (p = 0.001) between different soil layers at a 5% level of significance.

Soil texture and BD were the physical properties under investigation in the study area. Sandy loam texture was observed in the *S. robusta* forest. The result is in line with Bajracharya et al. (2007), who reported that the textural class of forest soil of Makawanpur district is sandy loam to silt loam. The study found that BD in *S. robusta* forest was increased with an increase in soil profile depths with an average BD of 1.16 $gmcm^{-3}$ throughout 1 m soil profile depth. The mean value is in line with the result of 1.17 $gmcm^{-3}$ as reported by Ghimire et al. (2018) in the *S. robusta* dominated forest in Makawanpur district, Nepal. Similarly, Kafle (2019) estimated that the mean value of BD was 1.28 $gmcm^{-3}$ in the *S. robusta* dominated community forests in Chitwan, Nepal. Furthermore, the BD depended on various factors such as compaction, consolidation and amount of organic matter present in the soil but was negatively correlated to the organic carbon content (Morisada et al. 2004).

Soil chemical properties

The average soil pH in the study area was 5.78, with pH throughout the soil profile ranging from 4.65 ± 0.77 to 6.5± 0.46. The maximum soil pH was recorded in the lower soil profile layer (i.e., 80-100 cm depth) and the minimum in the top soil profile layer (i.e., 0-20 cm depth). With the increase in depth, there was a gradual increase in soil pH (Table 2). The average TN, AP, and AK in 1 m soil profile depth in the *S. robusta* forest were 0.14 %, 5.94 $kgha^{-1,}$ and 104.20 $kgha^{-1,}$ respectively (Table 2). The highest amount of average TN, AP, and AK were recorded in 0-20 cm, and the lowest was found in 80-100 m depth (Table 2).

Table 1. Soil physical properties in *Shorea robusta* forest

Soil physical properties			**Fraction (%)**			
Texture	Sand		Silt	Clay		
	54.40± 5.07		30.14± 5.33	15.46± 3.01		
BD			Depths (cm)			*P* value
($gmcm^{-3}$)	0-20	20-40	40-60	60-80	80-100	
	1.03± 0.09	1.12± 0.07	1.18± 0.06	1.20± 0.05	1.29± 0.07	0.001*

Note:*p < 0.05 is considered statistically significant at a 5% level of significance

Table 2. Soil chemical properties in *Shorea robusta* forest

Soil chemical properties	**Depths (cm)**					***P* Value**
	0-20	**20-40**	**40-60**	**60-80**	**80-100**	
pH	4.65± 0.77	5.34± 0.80	6.02± 0.60	6.38 ± 0.48	6.50± 0.46	0.001*
TN (%)	0.21± 0.06	0.18± 0.05	0.13± 0.04	0.10± 0.04	0.07± 0.02	0.001*
AP($kgha^{-1}$)	10.62± 1.40	8.20± 0.90	5.70± 1.02	3.38± 1.09	1.80± 0.78	0.001*
AK($kgha^{-1)}$	166.84± 36.30	125.22± 24.96	98.90± 16.60	74.18± 8.78	55.85±11.68	0.001*

Note:*p < 0.05 is considered statistically significant at a 5% level of significance

Table 3. Correlation analysis of different variables

Variables	SOC stock	pH	BD	TN	AP	AK
SOC stock	1	-0.664*	-0.301*	0.601*	0.854*	0.793*
pH	-0.664*	1	-	-	-	-
BD	-0.301*	-	1	-	-	-
TN	0.601*	-	-	1	-	-
AP	0.854*	-	-	-	1	-
AK	0.793*	-	-	-	-	1

Note:*$p < 0.05$ is considered statistically significant at a 5% level of significance

Table 4. SOC content % and SOC stock in different soil layers

Soil depths (cm)	SOC content (%)	*P* Value	SOC stock (t/ha^{-1})	*P* Value
0-20	1.24± 0.11		25.78 ± 3.90	
20-40	1.01± 0.09		22.86 ± 2.51	
40-60	0.92± 0.11	0.001*	21.75± 3.24	0.001*
60-80	0.78± 0.09		19.10 ± 1.94	
80-100	0.69± 0.07		18.08 ± 2.90	
Total			107.57± 3.06	

Note:*$p < 0.05$ is considered statistically significant at a 5% level of significance

The studied chemical properties (pH, TN, AP, and AK) of the soil were found to be significantly different (p=0.001) between different soil layers at a 5% level of significance (Table 2). Furthermore, the study also revealed a significant relationship between the calculated variables. The pH of the forest soil was negatively correlated with SOC stock (r = -0.664; p = 0.001). However, SOC stock had strong positive correlation with TN (r = 0.601; p = 0.001), AP (r = 0.854; p = 0.001) and AK (r = 0.793; p = 0.001). Those indicate that SOC stock has a negatively strong correlation with soil pH. In contrast, TN has a moderate positive correlation, while AP and AK have a positively strong correlation with SOC stock (Table 3).

The soils in the study area were acidic, with an average pH of 5.78. Kafle (2019) reported average soil pH of 5.30 in the *S. robusta* dominated forest of Chitwan district, Nepal. Previous studies also revealed that moderately acidic soils dominate Nepal due to parent material (such as sandstone, siltstone, quartzite, and shale) and the atmospheric nature of aluminum in these soils (Ghimire and Bista 2016; Pandey et al. 2018). Similarly, the average TN, AP, and AK in the study area were in the range of 0.07 % to 0.21%, 1.80 to 10.62 kgha$^{-1,}$ and 55.85 to 166.84 kgha$^{-1,}$ respectively (Table 2). With the increase in soil depth, there was a gradual reduction in TN, AP, and AK throughout the soil profile depth. That could be attributed to increased uptake and less contribution of nitrogen, phosphorous, and potassium nutrients by the litters (Shrestha et al. 2004; Twongyirwe et al. 2013; Manpoong and Tripathi 2019;). The higher amount of soil nutrients like nitrogen, phosphorous, and potassium in the top soil profile can be accounted for by a considerable amount of litter decomposition and higher inputs of organic matter through litter fall (Manpoong and Tripathi 2019).

Soil organic carbon stock

Soil depth ($p < 0.05$) had a significant effect on both SOC content % and the SOC stocks in the *S. robusta* forest soil (Table 4). The average SOC content in *S. robusta* forest was recorded highest at the top soil layer, i.e., 0-20 cm depth with 1.24 ±0.11%, whereas the lowest was at 80-100 cm depth with 0.69 ±0.07% (Table 4). Accordingly, the total SOC stock within 1 m soil profile depth in *S. robusta* forest was 107.57 ±3.06 tha^{-1} (Table 4). Both SOC content and SOC stock were found higher at the upper layer of soil in all depth intervals. The greater the depth, the lower the organic carbon content and SOC stock in all depth intervals of *S. robusta* forest. For example, in 0-20 cm soil profile depth, SOC content and SOC stock were found to be 1.24 ±0.11% and 25.78 ±3.90 tha$^{-1,}$ respectively; whereas in 80-100 cm soil depth, it was reported 0.69 ±0.07% % and 18.08 ±2.90 tha^{-1} respectively (Table 4).

ANOVA test showed that both SOC content and SOC stock were significantly higher ($p \leq 0.001$) in the topsoil compared to the subsoil in the *S. robusta* forest (Table 3). Furthermore, the study found that BD of the forest soil was strongly negatively correlated with SOC stock (r = -0.301; p = 0.001). Those suggest that SOC stock negatively correlates weakly with soil pH (Table 3).

Forest soils are natural reserves and sinks of C and play an important role in sequestrating atmospheric carbon to mitigate global climate change (Wang et al. 2004; Lewis et al. 2009; Ghimire et al. 2018). The variables investigated for the analysis of SOC stock were soil BD and SOC content percentage (%). Significant variations in all tested variables were found among all the soil profile depths in the *S. robusta* forest (Table 3). The mean value of SOC content (0.93%) reported in the study was in line with that of Ghimire et al. (2018) and Kafle (2019), who reported SOC content of 0.99% and 0.95%, respectively, in *S. robusta* dominated community forest in Chitwan and

Makawnpur districts of Nepal respectively. Total SOC stock in 1 m soil profile depths of *S. robusta* was estimated to be 107.57 tha^{-1}. The finding was in line with the value 96.53 tha^{-1} and 110 tha^{-1} of SOC stocks in the *S. robusta* forest in Nepal, as reported by Gurung et al. (2015) and Ghimire et al. (2019), respectively.

Similarly, Kafle (2019) estimated a SOC stock of 122.36 tha^{-1} in the 1 m soil profile depth in *S. robusta* dominated community forest in Chitwan, Nepal. The modest range of variation could be due to difference in forest conditions, soil properties, soil sampling techniques, and management practices (Spurgeon et al. 2013; Kafle 2019). The higher concentration of SOC content and SOC stock were observed in the top soil layer, which could be attributed to higher soil organic matter content and less influence of parent materials (Dhakal et al. 2010). Pandey and Bhusal (2016) reported the declining trend of SOC stocks with the increase in soil depth in *S. robusta* dominated forests of hills and Terai regions of Nepal. Gautam and Mandal (2013) also reported a decreasing SOC content and SOC stock trend with increased soil depth in a tropical moist forest in eastern Nepal. Land use types and management practices significantly impact SOC and soil properties (Spurgeon et al. 2013; Ghimire et al. 2018; Ghimire et al. 2019).

In conclusion, this study was mainly focused on analyzing the vertical distribution of SOC stock and soil physicochemical properties within a 1 m soil profile depth in the *S. robusta* dominated community forest of Nepal. The study revealed the potential of *S. robusta* dominated community forest in C storage and enhancing soil physicochemical properties. The total SOC stock of the forest soil in 1 m soil profile depth was 107.57 tha^{-1}. Average TN, AP, and AK gradually decreased with increased soil profile depth. Soil profile depth had a significant effect on both SOC stock and soil physicochemical properties in forest soil.

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Taxonomy, distribution and statistical ecology of black mildew fungi reported from Maharashtra state of India

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Abstract. *Dubey R, Moonambeth N, Pandey AD. 2022. Taxonomy, distribution and statistical ecology of black mildew fungi reported from Maharashtra state of India. Asian J For 6: 97-125.* The Maharashtra state of India represents some of the best non-equatorial tropical forests in the world. It supports many endemic species of plants, animals, and microorganisms, especially in the Western Ghats, India. Moreover, a research project entitled "Foliicolous fungi of Maharashtra" was allotted by the Botanical Survey of India, Ministry of Environment, Forests, and Climate change, India, to carry out the mycological studies. As part of this project, ongoing studies were carried out on black mildew fungi of this state. The present studies offer a taxonomic account, distribution, and ecological parameters of 72 black mildew taxa collected from different areas of Maharashtra state of India. The present study provides three new records of fungi to India, 31 new host records to India, 40 new records of fungi to the Maharashtra state of India, and one new variety, viz., *Asterina jasmini* Hansf. var. *koyani* var.nov., depicted by checklist and Figures. In addition, a comprehensive table containing information on location, date of collection, name of the collector, and new records are given for ready reference. During this study, *Meliola* was the dominant genus with 35 species, whereas *Meliolina mollis* was the dominant taxon obtained from a maximum of 5 collections. More than 90% of black mildew species are collected from the Western Ghats Districts. In diversity indices, Gini-Simpson's was 0.9818, and Shannon's was 4.1668. Pielou's evenness index was 0.9743, causing true diversity, calculated as an effective number of species (64), to be less than observed species richness (72).

Keywords: Asterinales, checklist, diversity indices, Meliolales, new records, taxonomy

INTRODUCTION

The state of Maharashtra is located in the northwestern part of peninsular India. It lies between 15°35′N and 22°02′ N latitudes and 72°36′E and 80°54′E longitudes. Maharashtra occupies an area amounting to 307731 km2, which comprises about 9.4% of the total area of India. The elevation in the state ranges from sea level to 1646 m. The state may be divided into three natural divisions according to physiography, viz., the narrow coastal strip of land, known as Konkan, lying between the Arabian Sea and the Western Ghats, the Western Ghats, and the Deccan Plateau. The Western Ghats is considered one of the 'Biodiversity Hotspots' of the world (Myers et al. 2000), showing high endemism in flora and fauna. From Dhule and Nandurbar in the north to the districts of Sindhudurg and Kolhapur in the south, the Western Ghats in Maharashtra passes 13 districts. Vegetation of the state was classified by Champion and Seth (1968) into the following five categories; (i) Tropical semi-evergreen forests, (ii) Tropical moist deciduous forests, (iii) Tropical dry deciduous forests, (iv) Tropical thorn forests, (v) Littoral and swamp forests. Black mildews are a group of black colony-forming parasitic fungi; most are obligate biotrophs, but a few are necrotrophs and host-specific with a very narrow host range. Since these fungi do not cause any appreciable pathogenicity in plants, not much attention has been paid to this group. However, due to higher temperatures in the parts infected by black mildew colonies, plant respiration is higher, causing reduced photosynthetic efficiency due to the lower efficiency of chlorophyll, leading to effects such as lower production of total sugar.

Black mildews are especially abundant in the tropics (Hansford 1956) and mostly infest the dicotyledonous Angiosperms (>90%). In addition, they also infect monocotyledons, Gymnosperms, and Pteridophytes. Black mildew belongs to the family Meliolaceae, Asterinaceae, Englerulaceae, and Parodiopsidaceae in the Ascomycota. Order Meliolales contains more than 1,580 species (Hawksworth et al. 1995), most of which (1,400) are in the genus *Meliola* (Parbery and Brown 1986). Asterinaceous fungi are host specific because they must circumvent, tolerate and overcome the specific resistance factors of the particular host (Chandraprabha et al. 2011). The species concept of Asterinaceous fungi was based on the respective host plants and also on the morphological aspects of the fungus (Doidge 1942; Hansford 1946, 1956; Hosagoudar and Abraham 1996, Hosagoudar 2012). With its tropical climate and diverse flora, India provides favorable conditions for many black mildew fungi growth. Keys to the genera of black mildew fungi can be found in Muller and von Arx (1973), whereas species descriptions and illustrations are in monographic treatments by Hansford (1961, 1963).

The biogeographical distribution of Meliolaceae members in India was described and illustrated by Hosagoudar in Meliolales of India, published in three volumes (Hosagoudar 1996, 2008, 2013). Asterinales of

India is well studied and illustrated by Hosagoudar (2012). The Black mildew fungi were mainly studied from Mahabaleshwar (Satara) in Maharashtra (Patil et al. 2014; Bhise et al. 2015, 2021). Nilgiris, Anamalai, Seithur hills, Kothayar, etc., from Tamil Nadu; mainly from Kodagu in Karnataka; and most of the places in the Western Ghats of Kerala State. The Maharashtra state of India represents some of the best non-equatorial tropical forests in the world. It supports many endemic species of plants, animals, and microorganisms, especially in the Western Ghats. herefore, persistent efforts were put in by a team of researchers to explore Maharashtra's foliicolous fungi over six years, from 2010 to 2016. In the present study, various areas were visited in different forest ecosystems of Maharashtra, and the live leaves having black mildew infections were collected. The outcome is the present work in the form of the consolidated account of the Black mildew fungi of Maharashtra.

MATERIALS AND METHODS

Study area

During the field survey, all the major forest types within Maharashtra, India, were visited. However, priority was given to densely forested areas, as evident from the Maharashtra portion of the forest map of India (Forest Survey of India 2021), shown in inset (B) of Figure 1. These areas were prioritized as they are crucial from a conservation perspective, including Western Maharashtra (encompassing biodiversity hotspots of Western Ghats) and tiger reserves of Northern Maharashtra. The surveyed areas include protected areas of wildlife sanctuaries (WLS) viz., Bhimashankar WLS, Dajipur WLS, Koyna WLS, Phansad WLS, Radhanagari WLS, Toranmal WLS; national parks viz., Sanjay Gandhi National Park, Chandoli National Park; Tiger Reserves of Melghat and Pench. The surveyed areas also include forest areas of districts of Ahmednagar, Amravati, Kolhapur, Mumbai (Suburban), Nagpur, Nandurbar, Pune, Raigad, Ratnagiri, Sangli, Satara, Sindhudurg, and Thane.

Procedures

Infected plant parts were carefully noticed in the field, and field notes were made regarding their pathogenicity, nature of colonies, infection, locality, altitude, etc. In the field, each infected plant was collected separately in polythene bags. These infected plant parts were pressed neatly and dried in-between blotting papers. After ensuring their dryness, they were kept in the butter paper folders. GPS data of collection locations were recorded during field tours. The GPS data was used to make a survey map (Figure 1) with QGIS 2.8 Wien version for microscopic study. Scrapes were taken directly from the infected host and mounted in a 10% KOH solution. After 30 minutes, KOH was replaced by Lacto phenol, prepared according to Rangaswamy (1975). The host plants were identified by consulting the experts. The nail polish technique (Hosagoudar and Kapoor 1985) was used to study the entire colony in its natural condition. Digital images were taken using a Digital color CCD Camera (Nikon DS Fi1) attached to a Nikon eclipse 50i microscope with interference optics. All the foliicolous samples are maintained systematically in the Botanical Survey of India, Western Regional Centre Herbarium, Pune (BSI). Meliolales of India vols. I-III (Hosagoudar 1996, 2008, 2013) as Asterinales of India (Hosagoudar 2012) were consulted to identify Black mildew fungi. The documented genera and species were classified as per Index fungorum and Mycobank online database and the 10th edition of Dictionary of Fungi.

Data analysis

Aspects of microfungal ecology at the diversity indices level were analyzed, consistent with, for instance, Dubey and Pandey (2022a,b). First, at the level of diversity indices, information on several species and many isolates was combined to calculate two widely used measures of fungal diversity. Next, to calculate a measure of evenness, and finally, to calculate true diversity by converting Shannon's Index into an effective number of species.

Simpson's Index (Jost 2006) measures the probability of two randomly selected isolates belonging to the same species. It takes values from 0 to 1. The formula gives it:

$$\text{Simpson's Index } (D) = \sum_{i=1}^{S} {p_i}^2$$

Where p_i (= n_i/N) is the proportion of i^{th} species, n_i = number of isolates of i^{th} species, N = total number of isolates of all species, and S = number of distinct species. Thus, the lower the index value, the lower the probability of two isolates belonging to the same species, thus the higher the diversity, and vice versa. However, such an interpretation tends to be counterintuitive. Hence, its complement (1-D), known as Gini-Simpson's Index (Jost 2006), which follows naturally from the laws of probability, has been used, which is easy and intuitive in terms of interpretability, as higher values correspond to higher diversity.

$$\text{Gini Simpson's Index } (1\text{-}D) = 1 - \sum_{i=1}^{S} {p_i}^2$$

Shannon's Index (Jost 2006) quantifies the uncertainty (or entropy) associated with correctly predicting the species to which the next isolate belongs. Therefore, the higher the value, the more the uncertainty, thereby higher the diversity. It is calculated as follows:

$$H = \sum_{i=1}^{S} p_i \ln(1 / p_i)$$

Where: ln = natural logarithm, while others are the same as in Simpson's Index.

Pielou's evenness index. J' (Pielou 1995) is a measure of species evenness. It is a normalized Shannon's index, bounded by zero and one. Higher values correspond to more equitable distribution, with J'=1 representing perfectly equitable distribution where all species are equally abundant. It is given by:

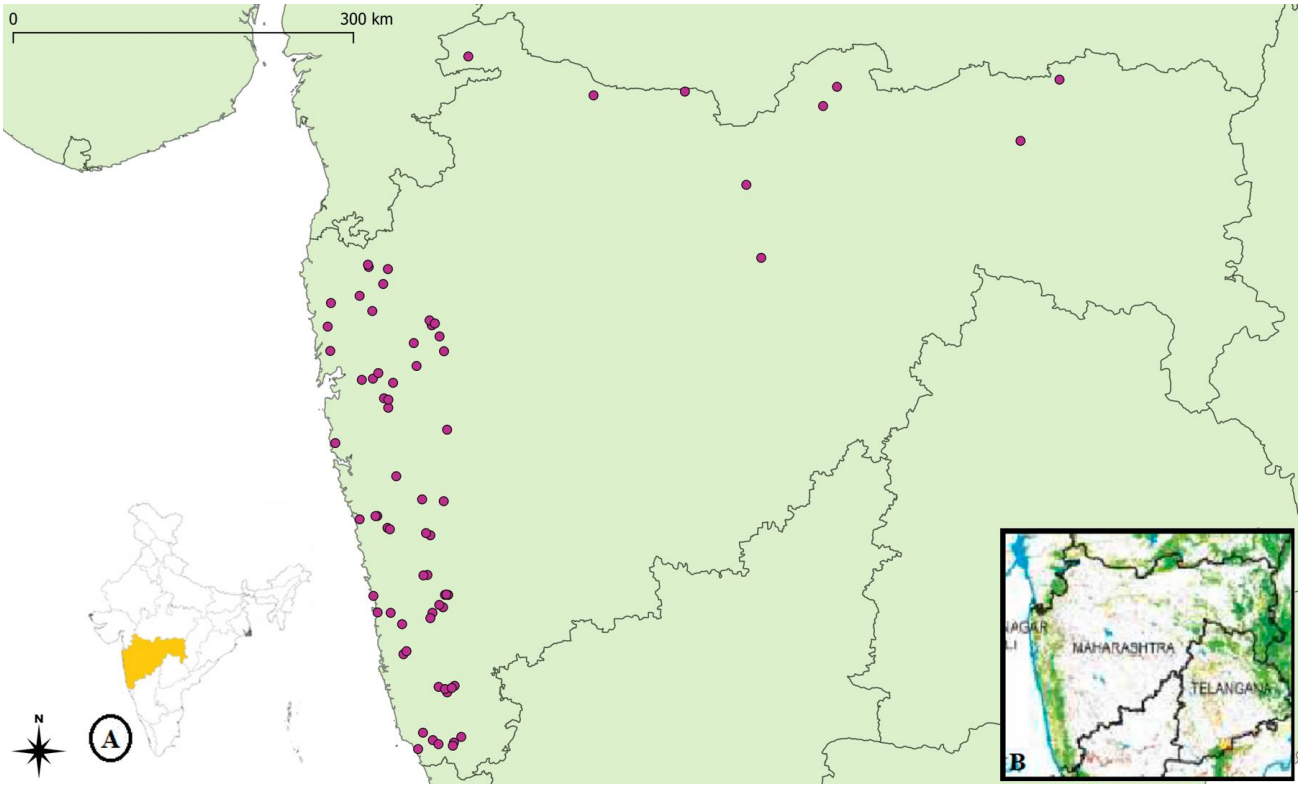


Figure 1. Collection locations in different districts of Maharashtra, India, and inset (A) Location of Maharashtra state in India (B) Forest map of Maharashtra, India (Source: Forest Survey of India 2021)

$$J' = \frac{H}{\ln(S)}$$

Next, we examine true diversity by calculating the effective number of species obtained by correcting species richness (observed number of species) by incorporating evenness (number of isolates). The effective number of species, calculated from a diversity index, is the equivalent number of equally abundant species in a hypothetical assemblage for the same value of the given diversity index (Gotelli and Ellison 2004). True diversity is obtained by transforming Shannon's Index (H) as follows (Jost 2006):

$$ENS_H = e^H$$

Where, ENS_H is the effective number of species, and 'e' is Euler's number or natural base. ENS_H is usually rounded down to the nearest integer for a meaningful interpretation. We use Shannon's Index (H) for calculation as it weighs both common and rare species equally, unlike Simpson's Index and species richness which overweigh common species and rare species, respectively (Gotelli and Ellison 2004).

MS Excel was used for the statistical analysis carried out in the present paper.

RESULTS AND DISCUSSION

Taxonomy and checklist of black mildew fungi identified

A total of 72 species, documented under 14 genera, were identified from 87 collections which are well illustrated in Figure 2 to Figure 73. The study provides 3 new records of fungi to India, 31 new host records to India, 40 new records to the Maharashtra state of India, and one var. nov. *Asterina jasmini* Hansf. var. *koyani* var. nov. (Table 1).

Amazonia elaeocarpi *Hosag., D.K. Agarwal, H. Biju & Archana, Indian Phytopath. 60 (1): 82 2007. Figure 2*

Fungi, Ascomycota, Pezizomycotina Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae.

Specimen examined: On the leaves of *Leea indica* (Burm. f.) Merr. (Vitaceae), Kesari, Sawantwadi Tal. Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200117 BSI (WC).

Remarks: This is the first instance of the fungus being encountered as foliicolous on the leaves of *L. indica*. Further, no species of Amazonia is reported on *L. indica*. Therefore, this is a new host record for India and a new fungus record in Maharashtra.

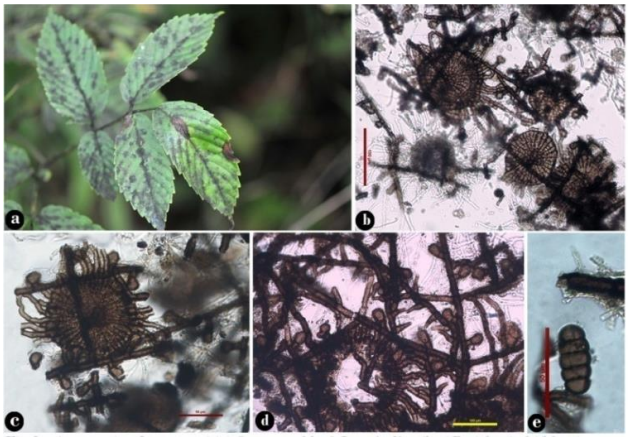


Figure 2. *Amazonia elaeocarpi* (a) Sooty mold of *Leea indica* (b-c) Perithecia hidden in radiating Mycelium (d) Mycelium with perithecia, appressoria, and phialides (e) Ascospore. [Scale bar: (b, d) = 100 µm; (c, e) = 50 µm.]

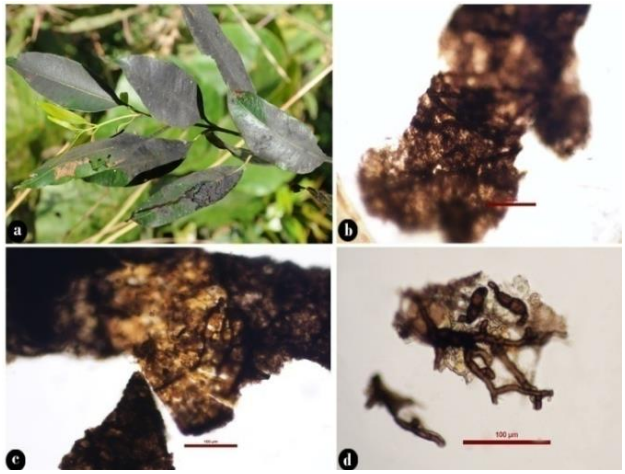


Figure 3. *Amazonia syzygii* (a) Sooty mold of *Syzygium cumini* (b-c) Perithecia hidden in radiating Mycelium (d) Ascospores. [Scale bar: (b-d) = 100 µm.]

Amazonia syzygii *Hosag. & Goos, Mycotaxon 36 (1): 236 1989. Figure 3*

Specimen examined: On the leaves of *Syzygium cumini* (L.) Steels (Myrtaceae), Location 1, Metindoli, Koyna WLS, Satara Dist., Maharashtra, India, 13.02.2015, RD, 201751 BSI (WC).

Known distribution: There are certain reports of association of the fungus on leaves of *S. cumini*, Kerala (Hosagoudar and Pillai 1993); on leaves of *Syzygium* sp., Tamil Nadu (Hosagoudar 1996).

Remarks: This is the first instance of fungus from the Maharashtra region of the Western Ghats.

Asteridiella depokensis *(Hansf.) Hansf., Sydowia 16 (1-6): 321 1963. Figure 4* = Irenina depokensis *Hansf., Reinwardtia 3 (1): 109 1954)*

Fungi Ascomycota, Pezizomycotina Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae.

Specimen examined: On the leaves of *Vitex negundo* L. (Lamiaceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200081 BSI (WC).

Known distribution: On leaves of *V. negundo* (Verbenaceae), Hoddur, C. Jagath Thimmaiah (Thimmaiah et al. 2013).

Remarks: This is the first record of the fungus in Maharashtra state.

Asteridiella malloticola *(W. Yamam.) Hansf., Beih. Sydowia 2: 211 1961.* = Irenina malloticola *W. Yamam., Trans. Nat. Hist. Soc. Formosa 30: 415 1940. Figure 5*

Specimen examined: On the leaves of *Mallotus Philippensis* (Lam.) Muell Arg. (Euphorbiaceae), Location 2, Kusapur, Koyna WLS, Satara Dist., Maharashtra, India, 13.02.2015, RD, 201772 BSI (WC).

Known distribution: Reported on leaves of *M. philippensis* from Kerala (Hosagoudar and Goos 1989).

Notes: A total of 33 species of *Asteridiella* have been reported from India.

Remarks: This is the first record of the fungus in the Maharashtra region of the Western Ghats.

Figure 4. *Asteridiella depokensis* (a) Black mildews of *Vitex negundo* (b-c) Perithecia with mammiform wall (d-e) Mycelium with appressoria & phialides (f-g) Ascospores. [Scale bar: (b-c) = 100 µm, (d-g) = 50 µm.]

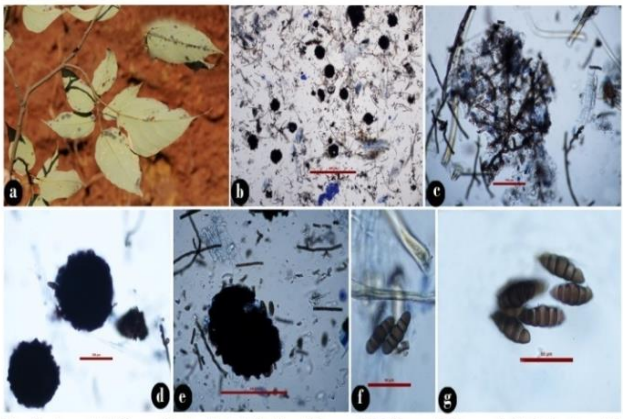


Figure 5. *Asteridiella malloticola* (a) Black mildews of *Mallotus philippensis* (b) Colonies with Perithecia (c) Mycelia with both appressoria & Phialides (d-e) Perithecia with ascospores (f-g) Ascospores. [Scale bar: b = 500 µm, (c-e) = 100 µm, (f-g) = 50 µm.]

Asterina capparis *Syd., P. Syd. & E.J. Butler [as'capparidis'], Annls mycol. 9 (4): 390 1911. Figure 6*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Dothideomycetidae, Asterinales, Asterinaceae.

Specimen examined: On the leaves of *Capparis* sp. (Capparaceae), Amboli Ghat, Sindhudurg Dist., Maharashtra, India, 22.01.2012, RD, 200224 BSI (WC).

Known distribution: Earlier reported on various species of *Capparis* from Karnataka, Tamil Nadu, and Uttar Pradesh (Maheshwari et al. 2012).

Remarks: This is the first record of the fungus in Maharashtra state.

Asterina delicatula *Syd., P. Syd. & Bal in Sydow, Annls mycol. 19 (5-6): 308 1921). Figure 7*

Specimen examined: On the leaves of *Jasminum* sp. (Oleaceae), Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200075 BSI (WC).

Known distribution: Reported on *Aegle marmelos* (L.) Corrêa from India (Hosagoudar 2012)

Remarks: This is the first record of the fungus in Maharashtra state, and also *Jasminum* sp. is a new host genus for *A. delicatula*.

Asterina henianii *Verma, Tripathi & Chaudhary Indian Phytopath. 52 (4): 377 1999. Figure 8*

Specimen examined: On the leaves of –

Syzygium sp. (Myrtaceae), Location 1, Dajipur WLS, Kolhapur Dist., Maharashtra, India, 09.02.2015, RD, 177201620 BSI (WC).

Syzygium cumini (L.) Skeels (Myrtaceae), Location 2, Dajipur WLS, Kolhapur Dist., Maharashtra, India, 09.02.2015, RD, 201642 BSI (WC).

Known distribution: Review of the literature reveals that *A. henianii* is reported on leaves of *Syzygium henianum* (Myrtaceae), Uttar Pradesh (Verma et al. 1999).

Remarks: This is the first record of the fungus from Maharashtra.

Asterina hydrocotyles *Hosag. & CK Biju Indian Phytopath. 58 (2): 198 2005. Figure 9*

Fungi Ascomycota, Pezizomycotina Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae.

Specimen examined: On the leaves of *Lawsonia inermis* L. (Lythraceae), Junnar, Pune Dist., Maharashtra, 21.09.2013, RD, 196234 BSI (WC).

Known distribution: Earlier reported on leaves of *Hydrocotyle* sp., Kerala and Tamil Nadu (Hosaguadar, 2012); on leaves of *Hydrocotyle javanica* Thumb. (Nithyatharani 2008).

Remarks: This is the first record of the fungus in Maharashtra, and also, *L. inermis* forms a new host genus record for *A. hydrocotyles.*

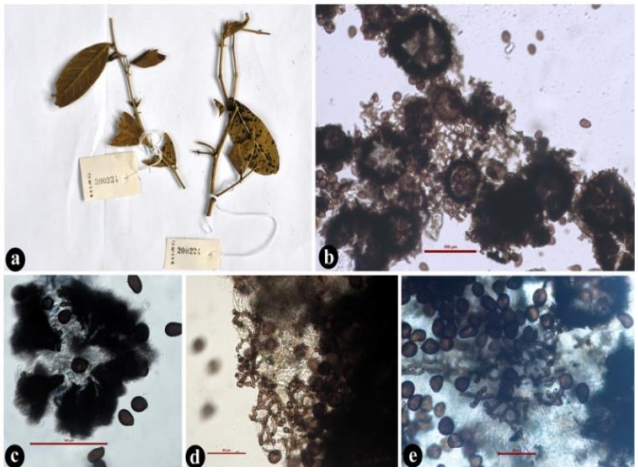


Figure 6. *Asterina capparis* (a) Black mildews of *Capparis* sp. (b) Colonies with Thyriothecia and Pycniothyria (c) Pycniothyria with pycnothyriospores (d-e) Pycnothyria with appressoria (e) Pycnothyriospores. [Scale bar: (b-c) = 100 µm, (d-e) = 50 µm.]

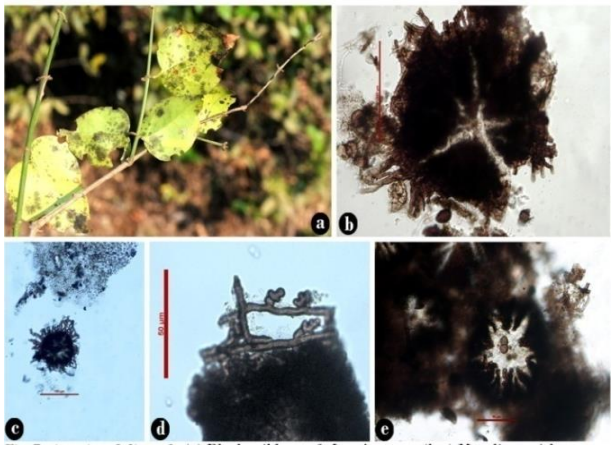


Figure 7. *Asterina delicatula* (a) Black mildews of *Jasminum* sp. (b-c) Mycelium with thyriothecia (d) Two-celled appressoria (e) Thyriothecia with ascospores. [Scale bar: (b-c) = 100 µm, (d-e) = 50 µm.]

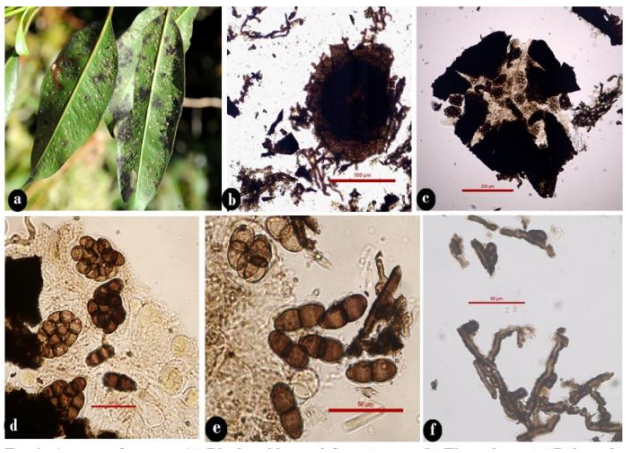


Figure 8. *Asterina henianii* (a) Black mildews of *Syzygium* sp. (b) Thyrothecia (c) Dehisced thyriothecia (d) Ascus (e) Ascospores (f) Mycelium with Appresoria.[Scale bar : b = 100 µm, c = 200 µm, (d-f) = 50 µm.]

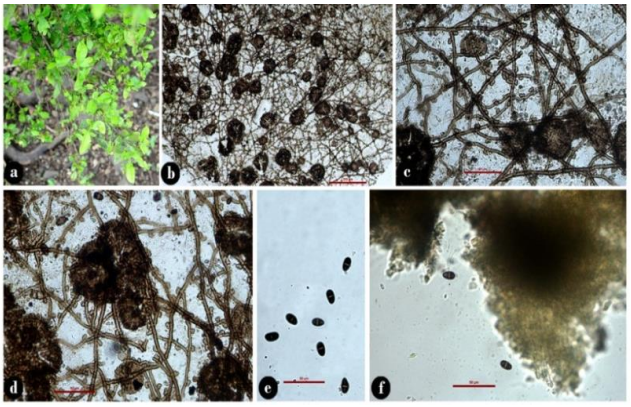


Figure 9. *Asterina hydrocotyles* (a) Infected leaves of *Lawsonia inermis* (b) Mycelia with thyriothecia and appressoria (c) Thyriothecia with appressoria and phialides (d) Pycno-thyria with pycnothyriospores (e-f) Pycnothyriospores with a hyaline band at the center.[Scale bar : b = 200 µm, (c-f) = 50 µm.]

Asterina jambolanae *A.K. Kar & Maity. Trans. Br. mycol. Soc. 54 (3): 438 (1970). Figure 10*

Specimen examined: On the leaves of *Eugenia* sp. (Myrtaceae), Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200100 BSI (WC).

Known distribution: India – Asterinales of India by Hoasagoudar (2012) referenced the distribution of *A. jambolanae* from Kerala, Karnataka, Uttar Pradesh, Tamil Nadu, and West Bengal (Hosagoudar 2012).

Remarks: This is the first record of the fungus in Maharashtra.

Asterina jasmini *Hansf. var. koyani var. nov. Rashmi Dubey Figure 11*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Dothideomycetidae, Asterinales, Asterinaceae

Specimen examined: On living leaves of *Jasminum malabaricum* Wight. (Oleaceae), Chandoli National Park, Maharashtra, India, 12.02.2015, Holotype, RD, 201731 BSI (WC).

Diagnostic features: *A. jasmini* Hansf. is distinct from other species of *Asterina* (known in the family Oleaceae) in having unicellular appressoria. The *A. jasmini* var. koyani differs from other species of *A. viz. A. jasmini* var. *indica* and *A. jasmini* var. *jasmini.* It has highly dissolved thyrothecia and echinulate ascospores. Therefore, it is justified to assign it as a new variety.

Notes: No species of *Asterina* and *Asterostomella* have been reported on J. malabaricum from India.

Remarks: Thus, this is the first report on the association of *A. jasmini* and its pycnothyrial stage (Asterostomella) with J. malabaricum from India and *A. jasmini* Hansf. var. koyani is a new variety for science.

Asterina jasminicola *Yates, Philippine J. Sci. 13: 373 1918; Maity, Indian J. Mycol. Res. 16: 24 1978. Figure 12*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Dothideomycetidae, Asterinales, Asterinaceae.

Specimens examined: On the leaves of *Jasminum multiflorum* (Burm. f.) Andrews (Oleaceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200080 BSI (WC).

Known distribution: The fungus has been reported earlier on leaves of *Jasminum pubescens* Willd (Oleaceae), West Bengal, Howrah, and Panchla (Maity 1978).

Remarks: This is a new record of the fungus in Maharashtra.

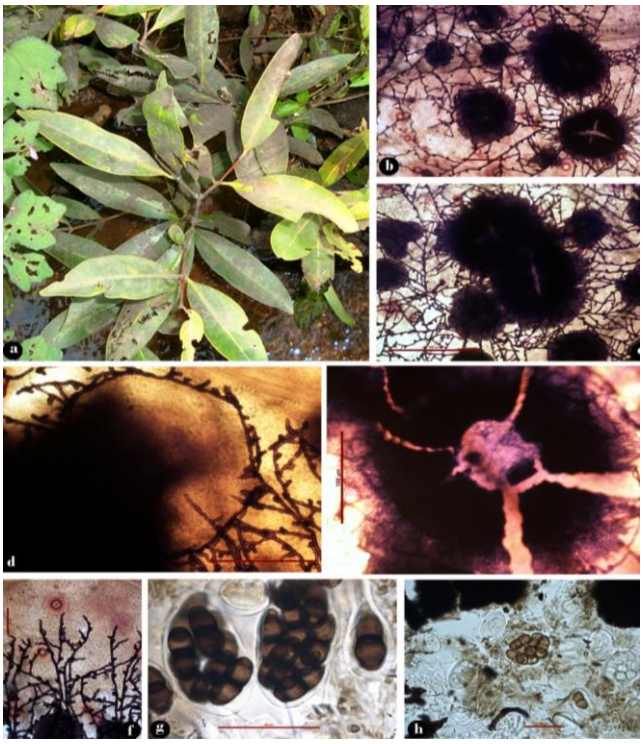


Figure 10. *Asterina jambolanae* (a) Black mildews of *Eugenia* sp. (b-c) Appresoriate mycelia with thyriothecia (d) young thyriothecia (e) Dehisced thyriothecia with ascospores (f) Mycelial Appressoria (g-h) Asci & ascospores. [Bar : (b-d) = 200 µm, (e-f) = 100 µm, (g-h) = 50 µm.]

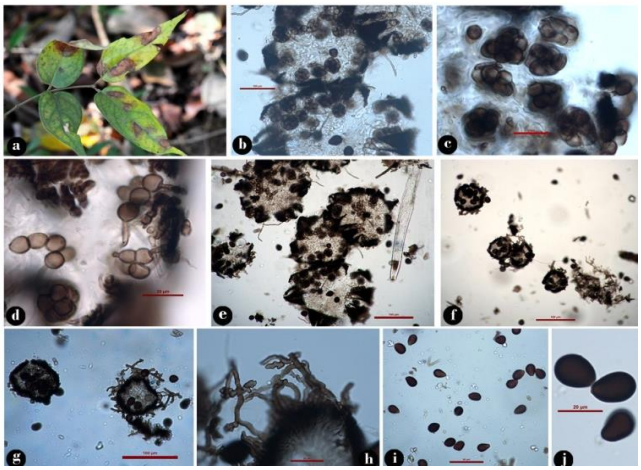


Figure 11. *Asterina jasmini var. koyani var. nov.* (a) Infected leaves of *Jasminum malabaricum* (b) Highly dissolved thyrothecia with asci (c) Asci (d) Echinulate ascospores (e-g) pycnothyria with pycnothyriospores (h) Bifid and deeply lobate unicelled appressoria (i-j) pycnothyriospores. [Bar : (b, e-g) = 100 µm, i = 50 µm, (c, d, h, j) = 20 µm.]

Asterina morellae *Hosag., CK Biju & Abraham, Indian Phytopath. 54: 137 2001; Hosag., Zoos' Print J,. 21: 2328 2006; Hosag., Chandraprabha & Agarwal, Asterinales of Kerala, p. 123 2011. Figure 13*

Specimen examined: On the leaves of *Garcinia* sp. (Guttiferae), Location 2, Kusapur, Koyna WLS, Satara Dist., Maharashtra, India, 13.02.2015, RD, 201773 BSI (WC).

Known distribution: Earlier reported on living leaves of *Garcinia morella* from Thiruvananthapuram and Chemunji, Kerala (Hosagoudar 2012). There is a report of the occurrence of other species of *Asterina* viz. *A. garciniae* Hansf. and *A. garciniicola* Ouyang & Song on *Garcinia* from India and China (Hosagoudar 2012).

Asterina woodfordiae *V.P. Sahni Mycopath. Mycol. appl. 23 (4): 330 1964. Figure 14*

Specimen examined: On the leaves of *Woodfordia fruticosa* (L.) Kurz. (Lythraceae), on the way to Dahanu, Thane Dist., Maharashtra, India, 17.10.2012, RD, 201106 BSI (WC).

Known distribution: On leaves of *Woodfordia floribunda* from Radhanagri, Maharashtra (Thite and Kulkarni 1975) and on leaves of *W. fruticosa*, Jabalpur, MP (Sahni 1964)

Remarks: The fungus is reported after 40 years in Maharashtra state**.**

Asterina wrightiae *Syd. Annls mycol. 29 (3/4): 236 1931. Figure 15*

Specimen examined: On the leaves of *Lagerstroemia* sp. (Lythraceae), Khandala, Pune Dist., Maharashtra, India, 26.09.2011, RD, 199560 BSI (WC).

Known distribution: Earlier reported on *Wrightia lanatus* (Sydow and Petrak 1931) from the Philippines. It has also been reported from various places in Kerala, India (Hosagoudar 2012).

Remarks: *Lagerstroemia* sp. forms a new host record for *A. wrightiae.*

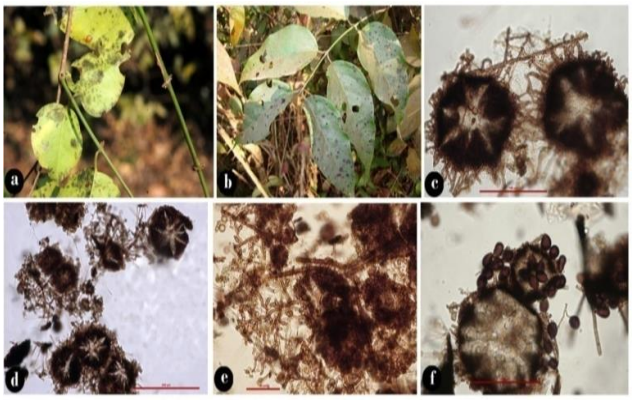


Figure 12. *Asterina jasminicola* – Black mildews of: (a) *Jasminum* sp. (b) *Jasminum multiflorum* (c) Thyriothecia with ascospores (d-e) Appresoriate mycelia with thyriothecia (f) Pycnothyria with pycnothyriospores. [Scale bar : e = 50 µm, d = 200 µm, (c,f) = 100 µm.]

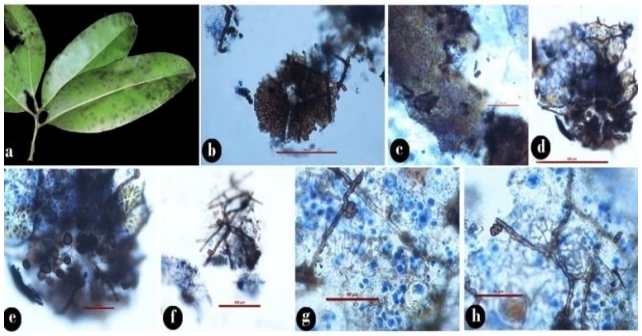


Figure 13. *Asterina morellae* (a) Black mildew of *Garcinia* sp. (b) Appresoriate mycelia with thyriothecia (c) Ascospores (d-e) Pycnothyria with pycnothyriospores (f-h) Sublobate to lobate appressoria. [Scale bars : (b, f) = 100 µm; (c, e, g, h) = 50 µm; d = 200 µm]

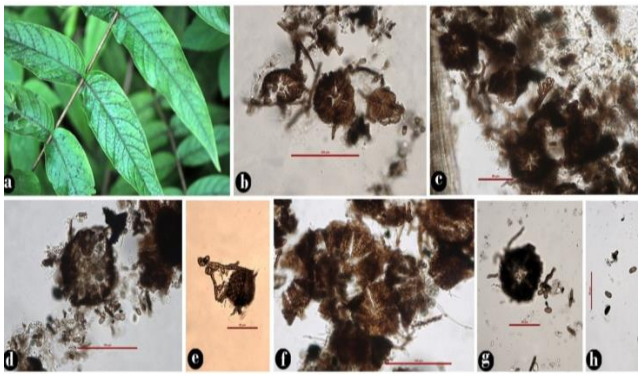


Figure 14. *Asterina woodfordiae* (a) Infected leaves of *Woodfordia fruticosa* (b-e) Appresoriate mycelia with thyriothecia (f) Thyriothecia with ascospores (g) Pycnothyria with pycnothyriospores (h) Pycnothyriospores. [Scale bars: (b, d, f) = 100 µm; (c, e, g, h) = 50 µm]

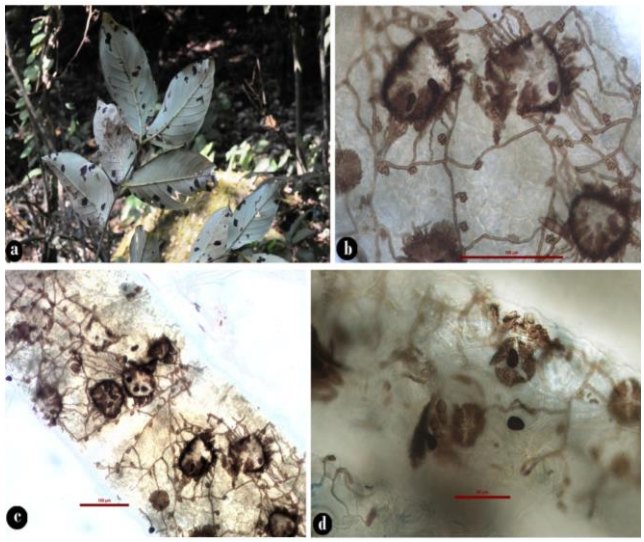


Figure 15. *Asterina wrightiae* (a) Black mildews of *Lagerstroemia* sp. (b-c) Appresoriate mycelia with thyriothecia and pycnothyria (d) Pycnothyria with pyriform pycnothyriospores. [Scale bars : (b, c) = 100 µm; d = 50 µm]

Asterina wrightii *Berk. & M.A. Curtis, Grevillea 4 (29): 10 (1875). Figure 16*

Specimen examined: On the leaves of *Paramignya monophylla* Wight, Forest Range, Dapoli, Ratnagiri Dist, Maharashtra, India, 26.01.2013, RD, 194051 BSI (WC).

Notes: Frequently reported on *Cucurbits*.

Remarks: It is a new record of fungal species from India.

Asterostomella *state of* Asterina jasmini *Hansf. Figure 17*

Specimen examined: On the leaves of *Jasminum* sp. (Oleaceae), Location 1, Chandoli National Park, Sangli Dist., Maharashtra, India, 11.02.2015, RD, 201688 BSI (WC).

Remarks: This is the first report of the occurrence of the Asterostomella state of *A. jasmini* on *Jasminum* sp. from India.

Asterostomella *state of* Asterina jasminicola *Yates. Figure 18*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Dothideomycetidae, Asterinales, Asterinaceae.

Specimen examined: On the leaves of *Jasminum* sp. (Oleaceae), Location 3, Chandoli National Park, Sangli Dist., Maharashtra, India, 11.02.2015, RD, 201708 BSI (WC).

Remarks: This is the first report of the occurrence of the Asterostomella state of *A. jasminicola* from India.

Asterostomula pavettae *V.B. Hosagoudar & A. Sabeena, Mycosphere 2 (5): 837 2007. Figure 19*

Fungi, Ascomycota, Pezizomycotina, Incertae sedis, Incertae sedis, Incertae sedis, Incertae sedis.

Specimen examined: On the leaves of *Pavetta* sp., Location 2, Kusapur, Koyna WLS, Satara Dist., Maharashtra, India, 13.02.2015, RD, 201776 BSI (WC).

Known distribution: on the leaves of *Pavetta tomentosa* Roxb. ex Smith (Rubiaceae), Kerala (Hosagoudar and Sabeena 2007).

Remarks: This is the first record of the fungus in Maharashtra.

Balladyna pavettae *Boedijin, Persoonia 1 (4): 398 1961. Figure 20*

Specimen examined: On the leaves of –

Synedrella nodiflora (L.) Gaertn. (Asteraceae), Akeri, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200026 BSI (WC).

Pavetta crassicaulis Bremek (Rubiaceae), Old Mahabaleshwar, Satara Dist., Maharashtra, India, 24.01.2012, RD, 200326 BSI (WC).

Known distribution: There is no report of the occurrence of *B. pavettae* from India. There is a report of the occurrence of fungus on the leaves of *Pavetta gardeniaefolia* from Java (Boedijin 1961).

Remarks: This is a new record of the fungal species in India.

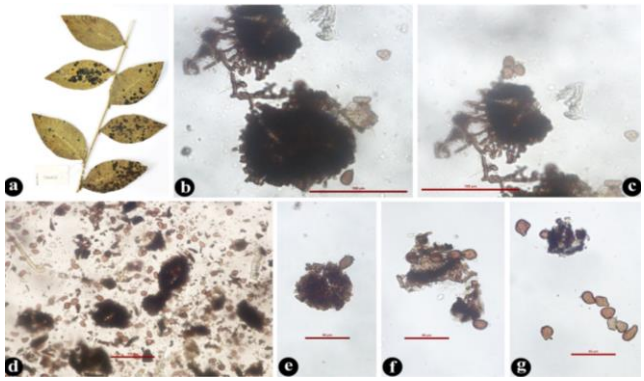


Figure 16. *Asterina wrightii* (a) Black mildews of *Paramignya monophylla* (b) Thyrothecia (c-e) Appresoriate pycnothyria with pycnothyriospores (f-g) Pycnothyriospores. [Scale bar : (b-d) = 100 µm; (e-g) = 50 µm]

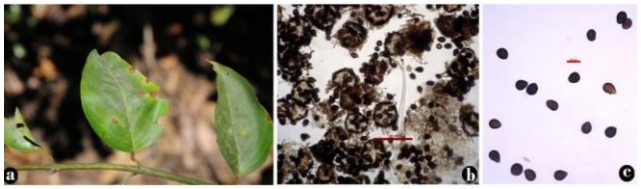


Figure 17. *Asterostomella state* of *Asterina jasmini* (a) Black mildew of *Jasminum* sp. (b) Pycnothyria (c) Pycnidiospores. [Scale bars: b = 100 µm; c = 50 µm]

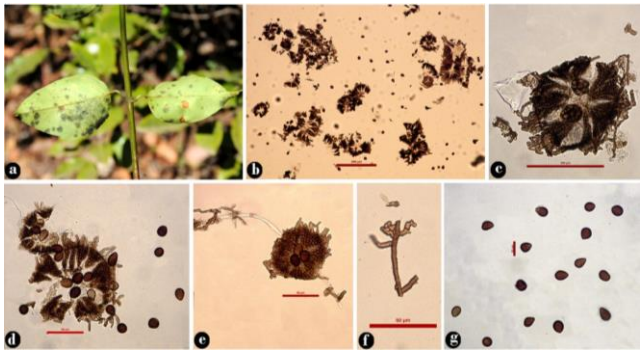


Figure 18. *Asterostomella* state of *Asterina jasminicola* (a) Black mildew of *Jasminum* sp. (b) Colony (c) Dehisced with ascus and ascospores (d) Dehisced Pycnothyria (e) Pycnothyria (f) Bicelled appressoria (g) Pycnothyriospores. [Scale Bar : b = 200 µm; c =100 µm; (d-f) = 50 µm; g = 20 µm]

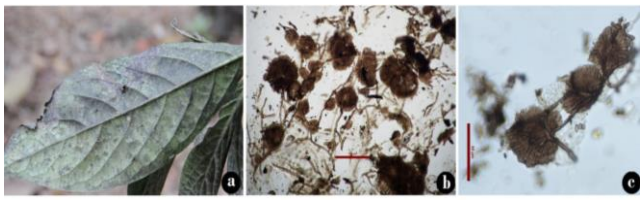


Figure 19. *Asterostomula pavettae* (a) Black mildews of *Pavetta* sp. (b) Mycelium with Pycnothyria (c) Pycnothyria with pycnothyriospores. [Scale bars: b = 100 µm; c = 50 µm]

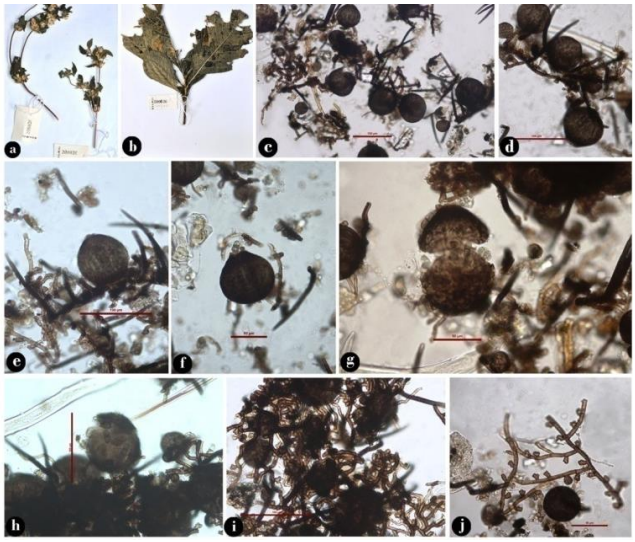


Figure 20. *Balladyna pavettae* - Black mildews of. (a) *Synedrella nodiflora* (b) *Pavetta crassicaulis* (c-d) Appresoriate mycelia with perithecia and setae (e-i) Perithecia with asci (j) mycelial appressoria. [Scale bar: (c-e), h,i = 100 µm; f,g,j = 50 µm]

Figure 21. *Balladyna ugandensis* (a) Black mildews of *Pavetta* sp. (b-c) Appresoriate mycelia with Perithecia (d) Mature perithecia with asci and ascospores. [Scale bar: b, d = 100 µm; c = 50 µm]

Balladyna ugandensis *Syd. & P. Syd. Annls mycol. 37 (3): 202 1939. Figure 21*

Specimen examined: On the leaves of *Pavetta* sp. (Rubiaceae), Teragaon, Bhimashankar, WLS, Pune Dist. Maharashtra, India, 28.09.2011, RD, 199628 BSI (WC).

Remarks: This is a new host record from India.

Balladyna vanderystii *(Hansf.) Arx in Müller & von Arx, Arx Beitr. Kryptfl. Schweiz 11 (no. 2): 186 1962. Figure 22*
Balladynopsis vanderystii *Hansf. 1957.*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Balladynaceae

Specimen examined: On the leaves of *Catunaregam spinosa* (Thunb.) Tirveng. (Rubiaceae), Kodawali-Rajapura, Ratnagiri, Maharashtra, India, 24.01.2013, RD, 200993 BSI (WC).

Known distribution**:** Earlier, the fungus was reported along with its teleomorphic and anamorphic stage (*Tretospora*) on living leaves of *lxora* sp. from Baharaich. U.P. (Jamaluddin et al. 2004).

Notes: The species was previously named *Balladyniopsis vanderystii* Hansf. As per the species fungorum, 2016 (CABI database), the current name of the fungus is *B. vanderystii*.

Remarks: This is the first record of the fungus in the Maharashtra region of the Western Ghats and a new host record from India.

Balladyna velutina *(Berk. & M.A. Curtis) Hohn Sber. Akad. Wiss. Wien, Math.-naturw. Kl., Abt. 1 119: 411 1910. Figure 23* =Asterina velutina *Berk. & M.A. Curtis, Proc. Amer. Acad. Arts & Sci. 4: 128 1860.*

Specimen examined: On the leaves of *Pavetta indica* L**.** (Rubiaceae), Location 2, Koyna WLS, Maharashtra, India, 13.02.2015, RD, 201769 BSI (WC).

Known distribution: This is one of the most common species in the Western Ghats region. Previously it was reported on living leaves of *P. indica*, Radhanagari (Patil and Thite 1977); Panhala (Thite and Kulkarni 1973, 1976). On leaves of *Psychotria nilgiriensis* Deb & M.G.Gangop., Kuthiraiyar, Kodaikanal, 2007, R. Nithyatharani; Periyakanal, shola forest, Kodaikanal, 2008, R. Nithyatharani (Hosagoudar 2012).

Remarks: This is reported from Satara Dist. of Maharashtra for the first time.

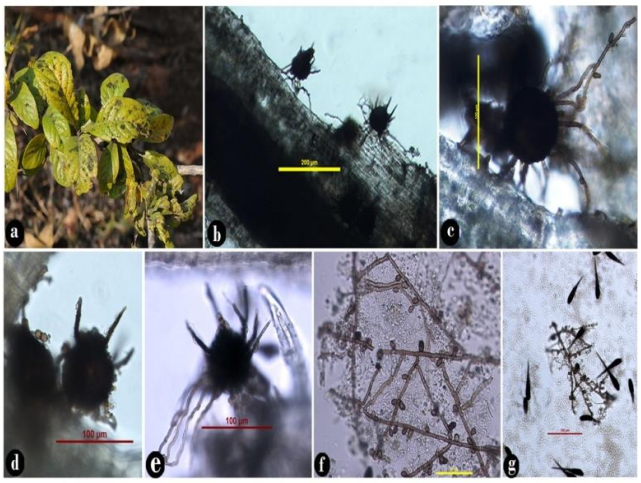


Figure 22. *Balladyna vanderystii* (a) Black mildews of *Catunaregum spinosa* (b-c) Appresoriate Perithecia (d-e) Perithecia with ascospores (f) Appressoria (g) Anamorphic state – Tretospora [Scale Bar: b = 200 µm; (c-e), g = 100 µm; f = 50 µm.]

Figure 23. *Balladyna velutina* (a) Black mildews of *Pavetta indica* (b-d) Appresoriate mycelia with perithecia and setae (e) Appresoria (f) young perithecia (g) Mature perithecia with ascospores

Cirsosia vateriae *Hosag., Mycosphere 2 (5): 799 2012. Figure 24*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Dothideomycetidae, Asterinales, Asterinaceae.

Specimen examined: On the leaves of Unidentified plant species no. 4, Matheran, Maharashtra, India, 27.09.2011, RD, 199600 BSI (WC).

Known distribution: Worldwide, 15 species of *Cirsosia* have been reported. Nationwide the known distribution of *Cirsosia* is as *Cirsosia globulifera* (Pat.) Arx is reported on *Calamus* sp. from TBGRI, Trivandrum, Kerala (Hosagoudar 1996), Kollam, Kerala (Hosagoudar 2003), and *C. arecacearum*. Hosagoudar and Pillai reported on *Calamus thwaitesii* Deb & M.G.Gangop. from Karnataka (Hosagoudar and Pillai 1993); *C. globulifera* is reported on leaves on *Calamus pseudotenuis* Becc. from Karnataka (Hosagoudar and Pillai 1993).

Remarks: This is the first record of the fungus in the Maharashtra region of the Western Ghats.

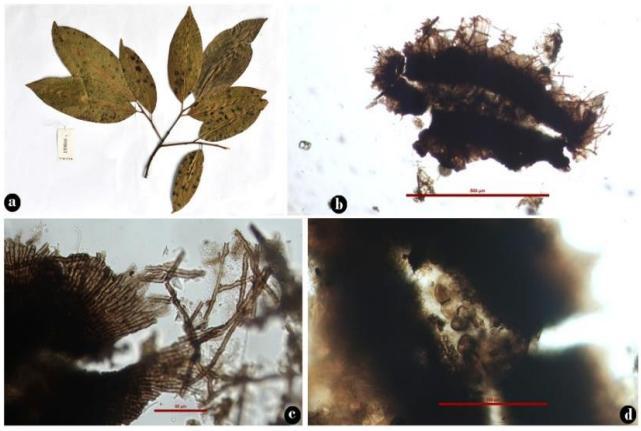


Figure 24. *Cirsosia vateriae* (a) On the leaves of Unidentified plant species (b) Longitudinally dehisced thyriothecia (c) Fimbriate margin of thyrothecia (d) Ascospores [Scale bar: b = 500 µm; c = 50 µm; d=100µm]

Meliola agrostistachydis *Hosag & Rajkumar J. Mycopathol. Res. 43 (1): 20 2005. Figure25*

Fungi, Ascomycota, Pezizomycotina Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae

Specimen examined: On the leaves of *Agrostistachys borneensis* Becc. (Euphorbiaceae). Location 1, Metindoli, Koyna WLS, Satara Dist., Satara Dist., Maharashtra, India, 13.02.2015, RD, 201745 BSI (WC).

Known distribution: India – Kerala (Hosagoudar 2008)

Remarks: This is the first record of the fungus in Maharashtra state.

Meliola allophyli-serrulati *Hosag. & T.K. Abraham J. Mycopathol. Res. 36 (2): 99 1998. Figure 26*

Specimen examined: On the leaves of *Allophylus* sp. (Sapindaceae), Fanaswadi, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200143 BSI (WC).

Known distribution: On the leaves of *Allophylus serrulatus* Raddlk., Kerala (Hosagoudar 2008); On *Allophylus cobbe* (L.) Forsyth fil. from Kerala (Maheshwari et al. 2012).

Notes: This is the first record of the fungus in Maharashtra state.

Meliola alstoniae *Koord Verh. K. Akad. Wet., tweede sect. 13 (4): 170 1907. Figure 27*

Specimen examined: On the leaves of Unidentified plant sp. 8, Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200157 BSI (WC).

Known distribution: On the leaves of *Alstonia scholaris* (L.) R.Br. from Goa (Thite and Kulkarni 1978), Kerala, Karnataka, and Tamil Nadu (Maheshwari et al. 2012).

Remarks: This is the first record of the fungus in Maharashtra.

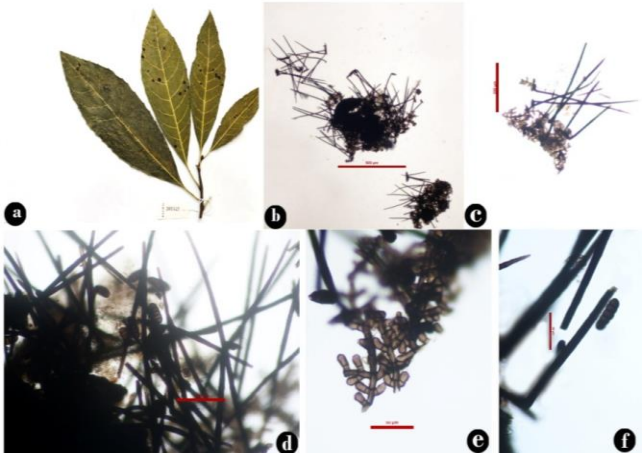


Figure 25. *Meliola agrostistachydis* (a) Black mildews of *Agrostistachys borneensis (*b) Perithecia with numerous setae (c) Perithecial setae (d) Setae with ascospores (e) Appresoria (f) Ascospores. [Scale bar: b = 500 µm; c = 200 µm; d = 100 µm; e, f =50 µm.]

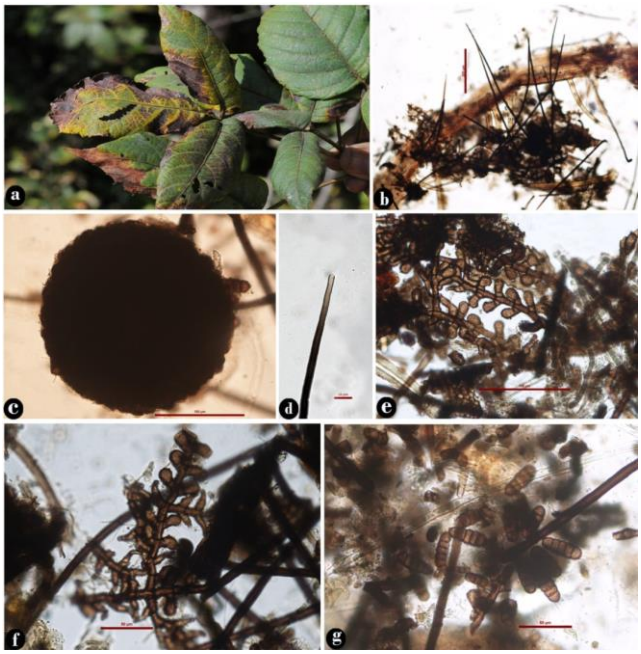


Figure 26. *Meliola allophyli-serrulati* (a) Black mildews of *Allophylus serrulatus* (b) Colonies (c) Perithecium (d) Apical portion of mycelial setae (e) Appresoria (f) Appresoria and phialides (g) Ascospores. [Scale bar: b = 200 µm; c, e = 100 µm; d = 20 µm; f, g = 50 µm.]

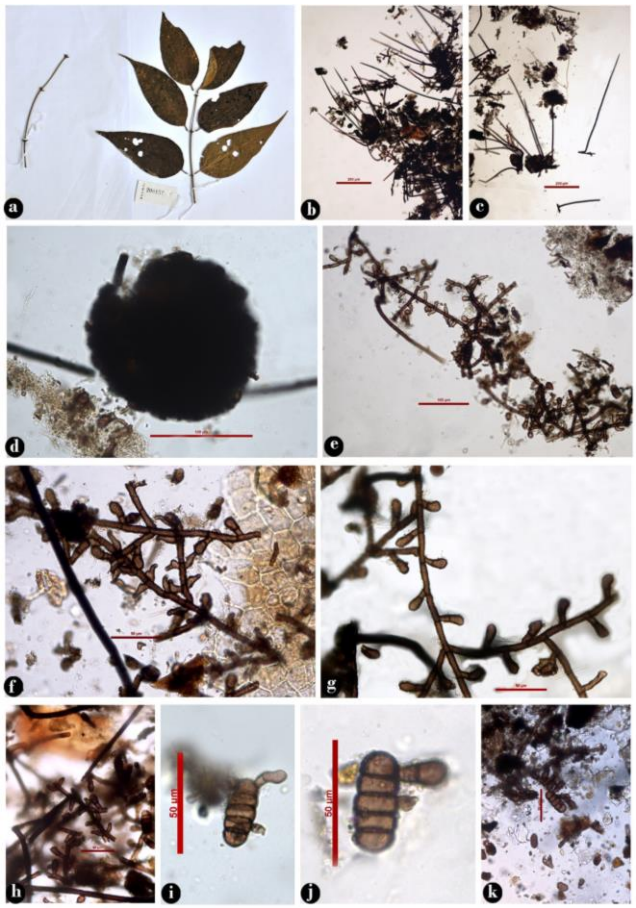


Figure 27. *Meliola alstoniae* (a) Black mildews of unidentified plant sp. (b-c) Colonies (d) Perithecium (e-h) Appresoria and phialides (i-k) Ascospores. [Scale bar: b, c = 200 µm; d, e =100 µm; (f-k) = 50 µm.]

Meliola bauhiniicola *W. Yamam., Trans. Nat. Hist. Soc. Formosa 31: 225 1941. Figure 28*

Fungi, Ascomycota, Pezizomycotina Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae

Specimen examined: On Bauhinia sp. (Leguminosae) leaves, Kurne-Lanje Tal. Reserved Forest, Ratnagiri Dist., Maharashtra, India, 24.01.2013, RD, 200988 BSI (WC).

Known distribution: On various species of *Bauhinia* from Andhra Pradesh, Kerala, Karnataka, and Maharashtra (Maheshwari et al. 2012).

Meliola buteae *Hafiz Khan, Azmatullah & Kafi, Biologia, Lahore 1(1): 112 1955. Figure 29*

Ascomycota, Pezizomycotina, Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae

Specimen examined: On the leaves of *Butea monosperma* (Lam.) Taub. (Leguminosae), Sanjay Gandhi National Park, Maharashtra, India, 25.09.2013, RD, 196384 BSI (WC).

Known distribution: On the leaves of *B. monosperma*, Kerala (Hosagoudar 1996), and Maharashtra (Thite and Patil 1982-1983).

Meliola careyae *(F. Stevens) Hosag. , Persoonia 18 (2): 276 2003. Figure 30*

Fungi, Ascomycota, Pezizomycotina Sordariomycetes, Incertae sedis, Meliolales, Meliolaceae

Specimen examined: On the leaves of *Careya arborea* Roxb. (Lecythidaceae), Akeri, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200022 BSI (WC).

Known distribution: On the leaves of *C. arborea* Roxb. from Karnataka (Hosagoudar 2008) and Kerala (Maheshwari et al. 2012).

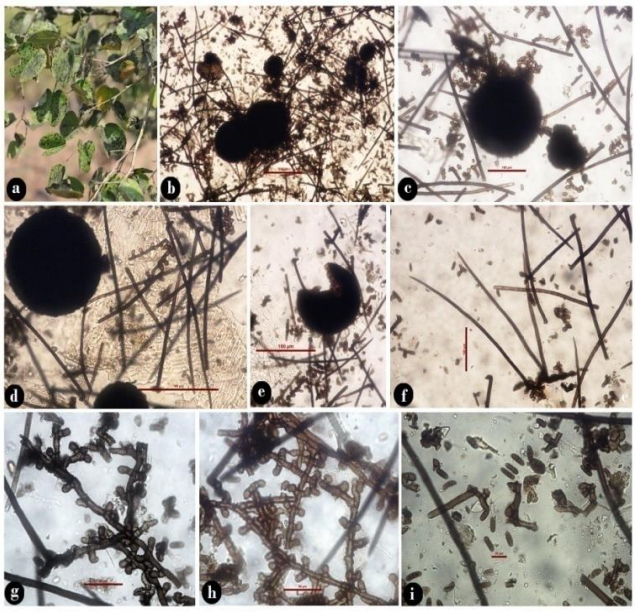


Figure 28. *Meliola bauhiniicola* (a) Black mildews of *Bauhinia racemosa* (b-e) Colonies with Perithecia (f) Setae (g-h) Appresoria and phialides (i) Ascospores. [Scale bar: b = 200 µm; (c-f) = 100 µm; g, h = 50 µm; i = 20 µm.]

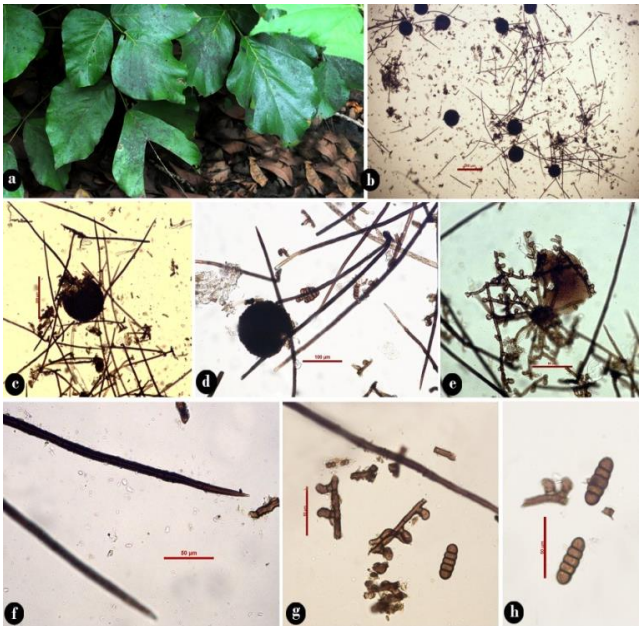


Figure 29. *Meliola buteae* (a) Black mildews of *Butea monosperma* (b) Colonies (c-d) Perithecium with setae and ascospores (e) Appresoria (f) Apical portion of mycelial setae (g) Phialides and Ascospores (h) Ascospores. [Scale bar: b,c = 200 µm; d = 100 µm; (e-h) = 50 µm.]

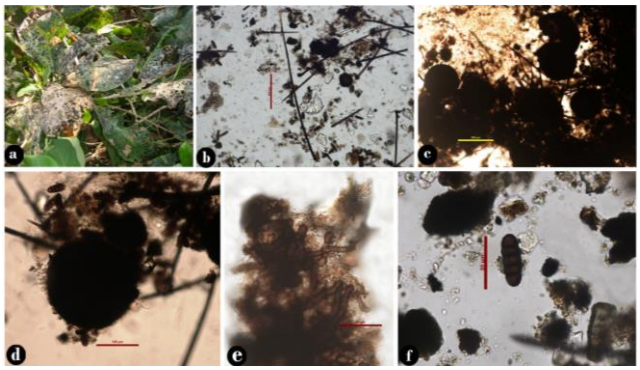


Figure 30. *Meliola careyae* (a) Black mildews of *Careya arborea* (b) Colonies (c-d) Perithecia (e) Appresoria and phialides (f) Ascospores. [Scale bar : b,c = 200 µm; d = 100 µm; (e-f) = 50 µm]

Meliola carissae *var.* spinari *Hosag. J. Econ. Taxon. Bot. 13 (1): 31 1989. Figure 31*

Specimen examined: On the leaves of *Carissa spinarum* L. (Apocynaceae), on the way to Jhap, Thane Dist., Maharashtra, India, 16.10.2012, RD, 201027 BSI (WC).

Known distribution: On leaves of *C. spinarum* (Apocynaceae), Uttar Pradesh, 1976, Kamal (Hosagoudar 1996); On leaves of *C. spinarum*, Coimbatore, Tamil Nadu (Hosagoudar 1989).

Remarks: This is the first record of the fungus in Maharashtra state.

Meliola desmodii-triquetri *Hosag. & Manojk in Hosagoudar, Zoos' Print Journal 19 (5): 1464 2004. Figure 32.*

Specimen examined: On the leaves of *Desmodium triflorum* (L.) DC. (Leguminosae), Akeri, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200010 BSI (WC).

Known distribution: On leaves of *Desmodium triquetrum* (L.) DC. (Fabaceae), from Kerala (Hosagoudar 2008) and Uttarakhand (Maheshwari et al. 2012).

Remarks: This is the first record of the fungus in Maharashtra state.

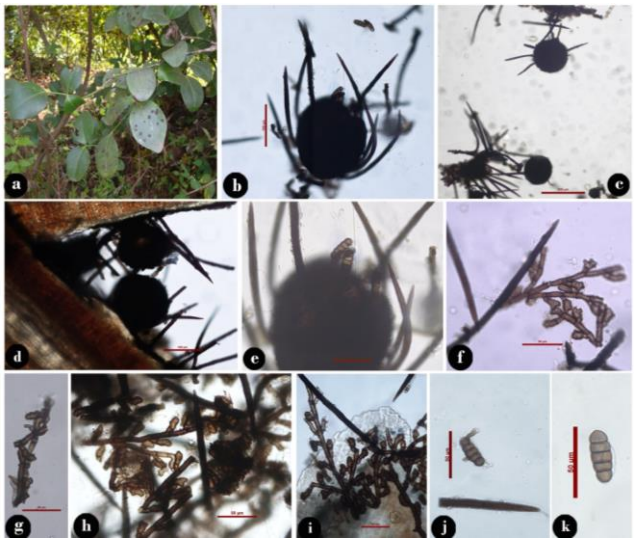


Figure 31. *Meliola carissae* var. *spinari* (a) Black mildews of *Carissa spinarum* (b-e) Perithecium with setae and ascospores (f-i) Appresoria and phialides (j-k) Ascospores. [Scale bar : b, d =100 µm; c = 200 µm; (e-k) = 50 µm]

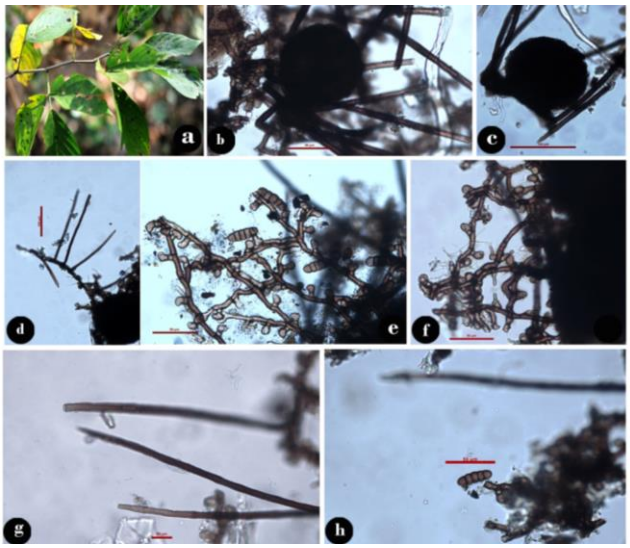


Figure 32. *Meliola desmodii-triquetri* (a) Black mildews of *Desmodium triflorum* (b,c) Perithecium with setae (d) Perithecial setae (e-f) Appresoria and ascospores (g) Apical portion of mycelial setae (h) Ascospores. [Scale bar: b, e, f, h = 50 µm; c, d = 100 µm; g = 20 µm.]

Meliola diospyri *H.S. Yates Syd. & P. Syd., in Sydow, Sydow & Butler, Annls mycol. 9 (4): 381 1911. Figure 33*

Specimen examined: On the leaves of *Diospyros* sp., (Ebenaceae), location 1, Dajipur WLS, Kolhapur District, Maharashtra, India, 09.02.2015, RD, 201629 BSI (WC).

Known distribution: On living leaves of *Diospyros* sp., Karnataka, Maharashtra (Patil and Thite 1978; Thite and Kukarni 1973).

Remarks: Recorded for the second time from the Western Ghats of Maharashtra after 40 years.

Meliola eugeniae-jamboloidis *Hansf., Reinwardtia 3: 98 1954. Figure 34* = Meliola eugeniae-jamboloidis *var.* amphigena *A.K. Kar & Maity, Nytt Mag. Bot. 17 (2): 87 1970.*

Specimen examined: On the leaves of *C. spinarum* (Apocynaceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200084 BSI (WC).

Known distribution: On leaves of *Syzygium munronii*, Sairandhri silent valley, Kerala (Hosagoudar 2008)

Remarks: This forms a new host record from India.

Meliola eugeniae-stocksii *Hosag. 1996 Figure 35*

Specimens examined: On the leaves of –

Ixora brachiata Roxb. (Rubiaceae), Amboli Ghat, Sindhudurg, Maharashtra, India, 22.01.2012, RD, 200178 BSI (WC).

Ficus sp. (Moraceae), Location 2, Radhanagari WLS, Kolhapur Dist., Maharashtra, India, 10.02.2015, RD, 201782 BSI (WC).

Ixora brachiata Roxb. (Rubiaceae), Fanaswadi, Sindhudurg, Maharashtra, India, 21.01.2012, RD, 200130 BSI (WC).

Remarks: This is the first record of the fungus in Maharashtra state.

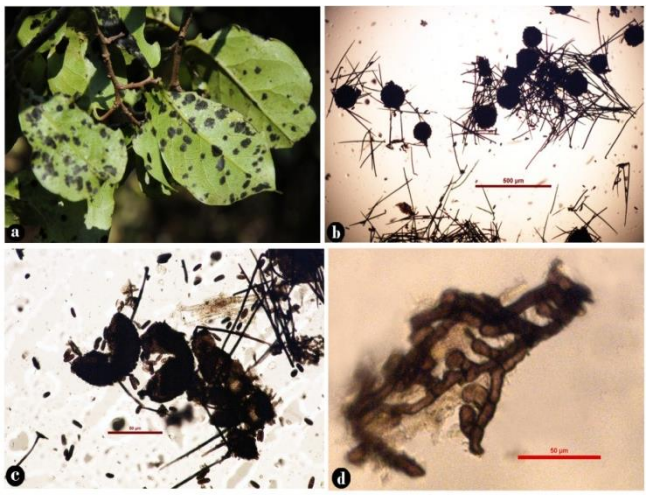


Figure 33. *Meliola diospyri* (a) Black mildews of *Diospyros* sp. (b) Colony (c) Perithecia with setae and ascospores (d) Mycelium with appressoria. [Scale bar : b = 500 µm; c, d = 50 µm.]

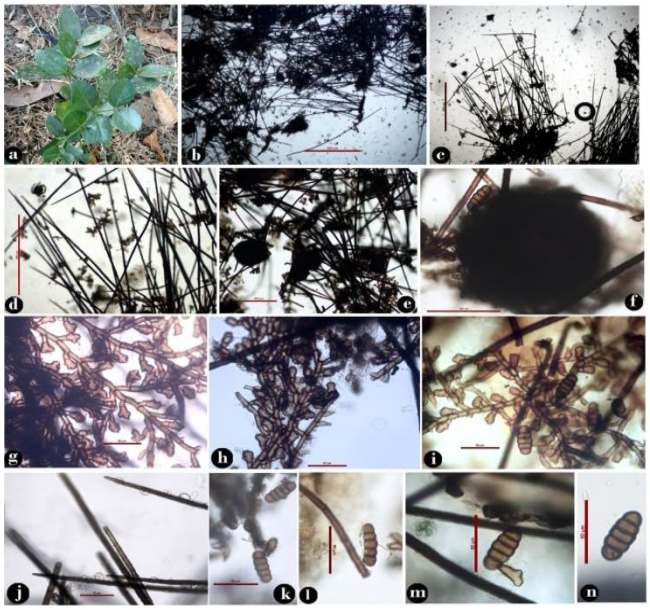


Figure 34. *Meliola eugeniae-jamboloidis* (a) Black mildews of *Eugenia* sp. (b-c) Colonies, (d-e) Perithecia with perithecial setae (f) Perithecium (g -i) Appresoria and phialides (j) Apical portion of mycelial setae (k-n) Ascospores. [Scale bar: (b-d) = 500 µm; e = 200 µm; f = 100 µm; (g-n) = 50 µm]

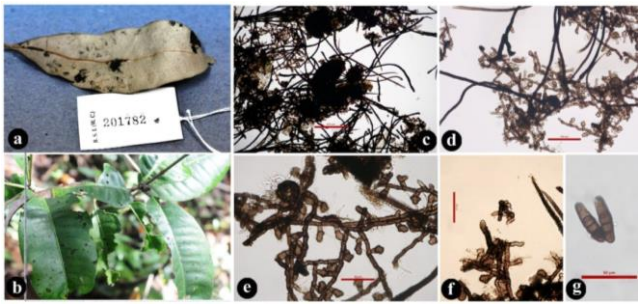


Figure 35. *Meliola eugeniae-stocksii* (a) Black mildews of *Ficus* sp. (b) Black mildews of *Ixora brachiata* (c) Perithecium with mycelia setae (d-e) Appresoria and phialides (f) Apical part of setae and phialides, (g) Ascospores. [Scale bar: c = 200 µm; d = 100 µm; (e-g) = 50 µm.]

Meliola flemingiicola *Hosag., Jose & H. Biju in Hosag., J. Mycopathol. Res. 43:26, 2005. Figure 36*

Specimen examined: On the leaves of *Lagerstroemia* sp. (Lythraceae), Pasarni Ghat, Satara Dist., Maharashtra, India, 25.01.2012, RD, 200371 BSI (WC).

Remarks: This is the first fungus record in Maharashtra and forms a new host record of fungi from India.

Meliola garhwalensis *S.L. Srivast. & Topal, Geophytology 11 (2): 264 1981. Figure 37* = Meliola rubi *var.* garhwalensis *(S.L. Srivast. & Topal) Hosag. & N.P. Balakr., in Hosagoudar, Patil & Balakrishnan, J. Econ. Taxon. Bot. 13 (1): 81 (1989).*

Specimen examined: On the leaves of *J. malabaricum* Wight. (Oleaceae), Old Mahabaleshwar, Satara Dist., Maharashtra, India, 24.01.2012, RD, 200335 BSI (WC).

Remarks: It is a new record for Maharashtra state and a new host record.

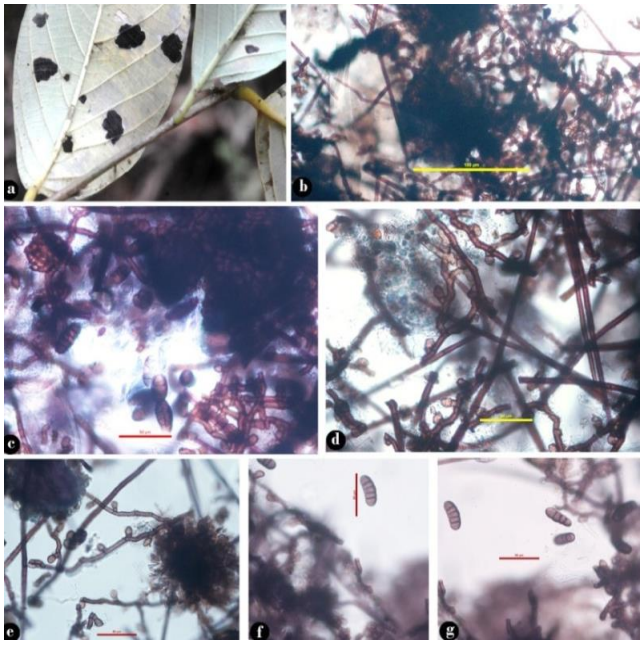


Figure 36. *Meliola flemingiicola* (a) Black mildews of *Lagerstroemia* sp. (b) Perithecia (c) Ascus with ascospores (d-e) Appresoria and phialides (f-g) Ascospores. [Scale bar: b = 100 µm, (c-g) = 50 µm.]

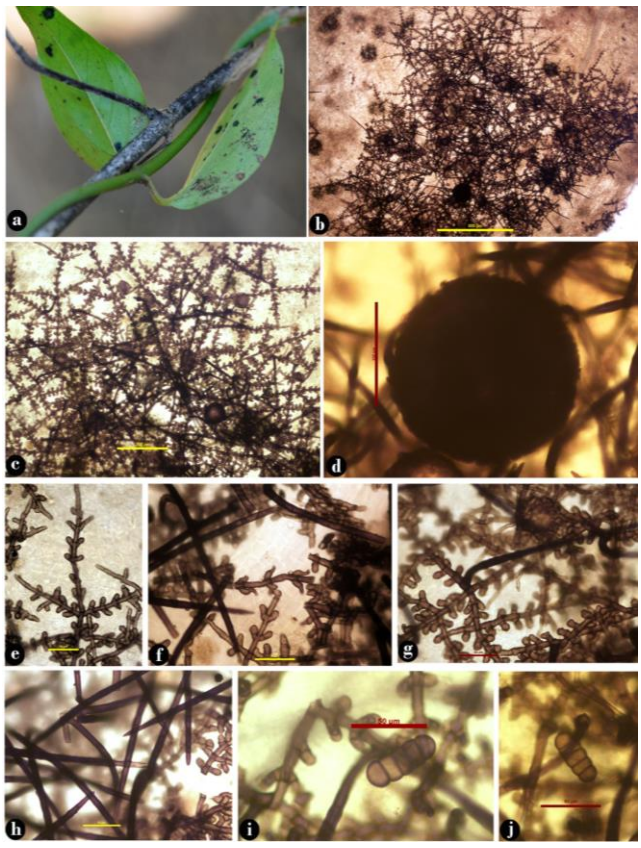


Figure 37. *Meliola garhwalensis* (a) Black mildews of *Jasminum malabaricum* (b-c) Colonies with opposite appressoria (d) Perithecium (e-g) Mycelium with setae appressoria and phialides (h) Mycelial setae (i-j) Ascospores. [Scale bar: b = 500 µm; c = 200 µm; d = 100 µm; (e-j) = 50 µm.]

Meliola hemidesmicola *Hosag, Meliolales of India (Calcutta): 212 1996. Figure 38*

Specimen examined: On Periplocaceae sp 2., Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200148 BSI (WC).

Known distribution: On leaves of *Hemidesmus indicus* (L.) from Kerala**,** Maharashtra, Tamil Nadu (Maheshwari et al. 2012).

Meliola holarrhenae *Hansf. & Thirum., Farlowia 3: 294 1948. Figure 39*

Specimen examined: On the leaves of *Holarrhena pubescens* (Buch. - Ham.) Wall. Ex DC. (Apocynaceae), Sanjay Gandhi National Park Maharashtra, India, 25.09.2013, RD, 196402 BSI (WC).

Known distribution: India- On leaves of *H. pubescens* from Karnataka and Kerala (Maheshwari et al. 2012).

Remarks: This is the first record of the fungus in Maharashtra state.

Meliola holigarnae *F. Stevens, Annls mycol. 26(3/4): 260 1928. Figure 40*

Specimen examined: On the leaves of *Holigarna* sp. (Anacardiaceae), Location 1, Metindoli, Koyna WLS, Satara Dist., Maharashtra, India, 13.02.2015, RD, 201754 BSI (WC).

Known distribution: On leaves of *Holigarna grahamii* (Wight) Kurz, Maharashtra (Thite and Kulkarni 1973); On leaves of *Holigarna* sp., Kerala, Karnataka, Tamil Nadu (in Maheshwari et al., 2012); On leaves of *Holigarna beddomei* Wall. ex Hook.fil., Karnataka; On leaves of *H. arnottiana*, Kerala; On leaves of *Holigarna* sp., Karnataka (Maheshwari et al. 2012).

Remarks: This is the second time reported from the Maharashtra state.

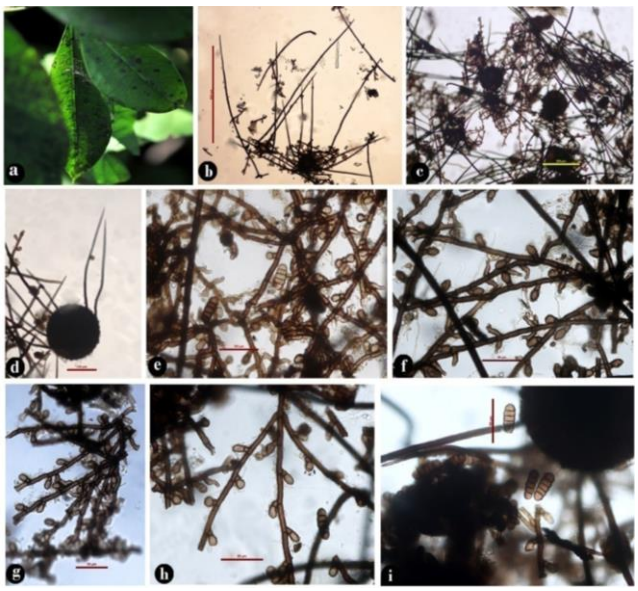


Figure 38. *Meliola hemidesmicola* (a) Black mildews of Periplocaceae sp. (b-c) Colonies (d) Perithecia (e-h) Appresoria and phialides (i) Ascospores. [Scale bar: b = 500 µm; c = 200 µm; d, e = 100 µm; (f-i) = 50 µm.]

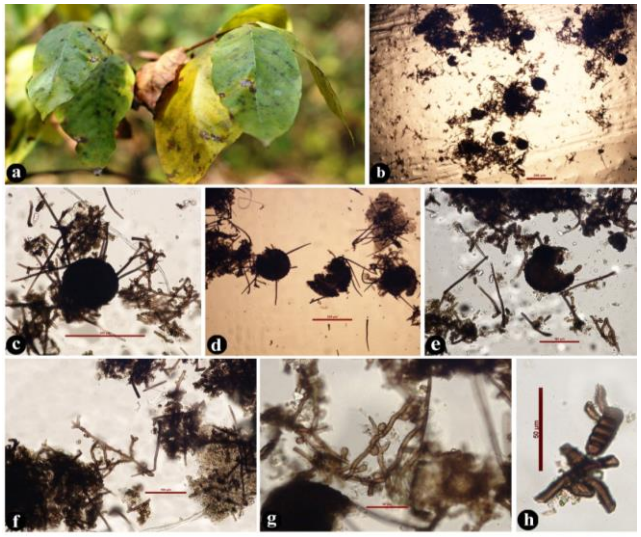


Figure 39. *Meliola holarrhenae* (a) Black mildews of *Holarrhena pubescens* (b) Colonies (c-e) Perithecia with mycelia setae and ascus (f-g) Appresoria and phialides (h) Ascospores. [Scale bar : (b-d) = 200 µm; e, f = 100 µm; g, h = 50 µm.]

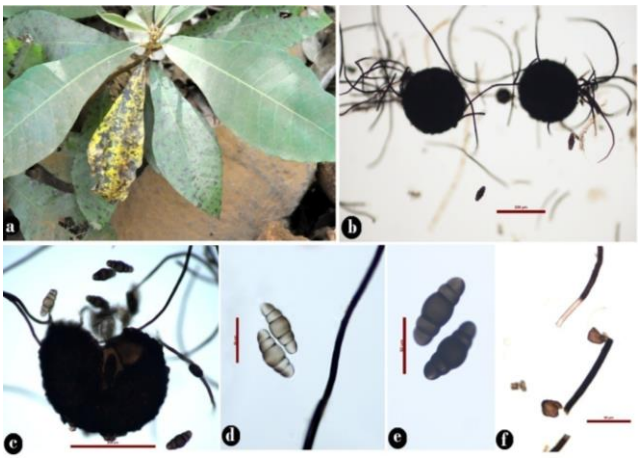


Figure 40. *Meliola holigarnae* (a) Black mildews of *Holigarna* sp. (b) Perithecia with mycelia setae (c) Perithecia with setae and ascospores (d-e) ascospores (f) Appresoria. [Scale bar : b, c = 200 µm; (d-f) = 50 µm]

Meliola hyptidis *Syd. & P. Syd., Annls mycol. 8 (1): 36 1910. Figure 41*

Specimen examined: On the leaves of –

Volkameria inermis L. (Lamiaceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200085 BSI (WC).

Plectranthus sp., (Lamiaceae), Sanjay Gandhi National Park, Mumbai, Maharashtra, India, 25.09.2013, RD, 196393 BSI (WC).

Remarks: Both above hosts form new host records for *M. hyptidis* from India.

Meliola ixorae *H.S. Yates, Philipp. J. Sci., C, Bot. 12: 365 1917. Figure 42*

Specimen examined: On the leaves of *Ixora* sp. (Rubiaceae), Location 2, Radhanagari WLS, Kolhapur Dist., Maharashtra, India, 10.02.2015, RD, 201662 BSI (WC).

Known distribution: Earlier reported on various species of *Ixora* from Kerala, Karnataka, and Maharashtra (Bilgrami et al. 1991; Maheshwari et al. 2012).

Meliola ixorae *Yates var. macrospora, Mycotaxon 37: 235 1990. Figure 43*

Specimen examined: On the leaves of –

Ixora brachiata Roxb. (Rubiaceae), on the way to Location 1, Amboli Ghat, Sindhudurg, Maharashtra, India, 22.01.2012, RD, 200215 BSI (WC).

Ixora brachiata Roxb. (Rubiaceae), Location 2, Amboli Ghat, Sindhudurg, Maharashtra, India, 22.01.2012, RD, 200180 BSI (WC).

Ixora coccinea L. (Rubiaceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200077 BSI (WC).

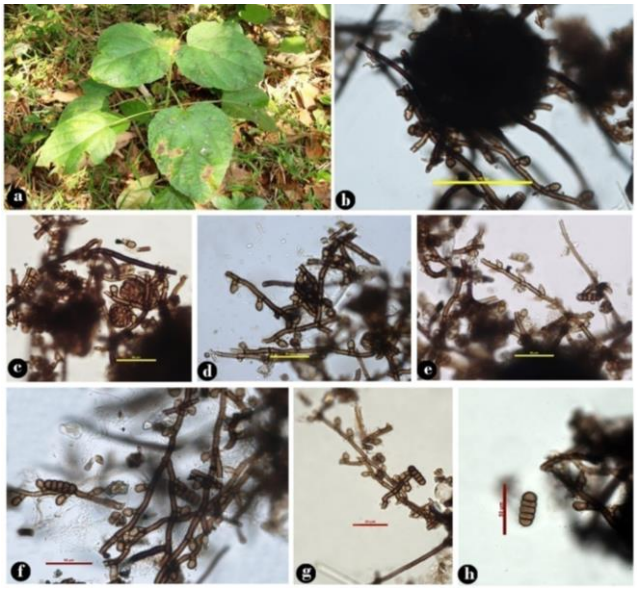


Figure 41. *Meliola hyptidis* (a) Black mildews of *Volkameria inermis* (b) Mature Perithecia (c) young Perithecia (d-e) Appresoria and phialides (f-g) Appresoria phialides & Ascospores (h) Ascospores. [Scale bar: b = 100 µm; (c-h) = 50 µm.]

Figure 42. *Meliola ixorae* (a) Black mildews of *Ixora* sp. (b) Colonies (c-d) Appresoria (e) Phialides (f) Ascospores. [Scale bar: b = 200 µm; (c-f) = 50 µm]

Figure 43. *Meliola ixorae* var. *macrospora* (a) Black mildews of *Ixora* sp. (b-c) Young perithecia (d-e) Mature perithecia with appressoria (f) Mycelial appressoria (g) Appresoria and phialides (h) Ascospores. [Scale bar: b, c = 200 µm; d, e = 100 µm; (f-h) = 50 µm]

Known distribution: On the leaves of *I. coccinea* (Rubiaceae) Radhanagari, Maharashtra, India, 1970, AN Thite (Hosagoudar 1996).

Remarks: *I. brachiata* forms a new host record from India.

Meliola ixorae-coccineae *Hosag. & C.M. Pillai, in Hosagoudar, Raghu & Pillai, Nova Hedwigia 58 (3-4):539 1994. Figure 44*

Specimen examined: On the leaves of –

Ixora brachiata Roxb. (Rubiaceae), Amboli Ghat, Sindhudurg, Maharashtra, India, 22.01.2012, RD, 200180 BSI (WC).

Ixora sp. (Rubiaceae), Location 1, Dajipur WLS, Kolhapur district, Maharashtra, India, 09.02.2015, RD, 201626 BSI (WC).

Known distribution: On leaves of *I. coccinea* (Rubiaceae), Kerala, 14 September 1992, C.M. Pillai (Hosagoudar 1996).

Remarks: This is a new host record for the fungus from India.

Meliola jasminicola *Henn. Hedwigia 34: 11 1895. Figure 45*

Specimens examined: On the leaves of –

Jasminum multiflorum (Burm. f.) Andrews (Oleaceae), Location 1, Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200080 BSI (WC).

Strychnos nux-vomica L. (Loganiaceae), Location 2, Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200083 BSI (WC).

Known distribution: On *Jasminum* sp. from Karnataka, Kerala, and West Bengal (Maheshwari et al. 2012)

Remarks: Both hosts mentioned above form a new host record from India.

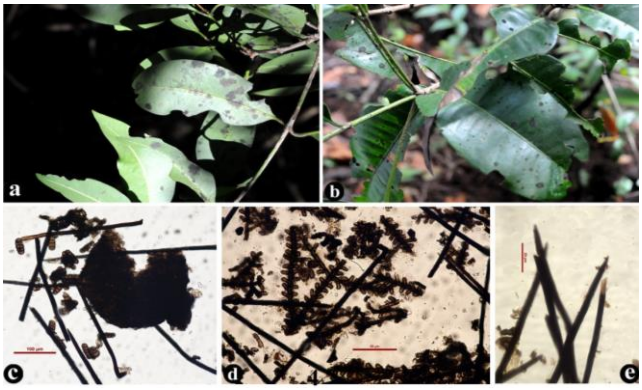


Figure 44. *Meliola ixorae-coccineae* (a) Black mildews of *Ixora* sp. (b) Black mildews of *Ixora brachiata* (c) Perithecium with setae and ascospores (d) Mycelium with appressoria (e) Mycelial setae. [Scale bar : c = 100 µm; d, e = 50 µm]

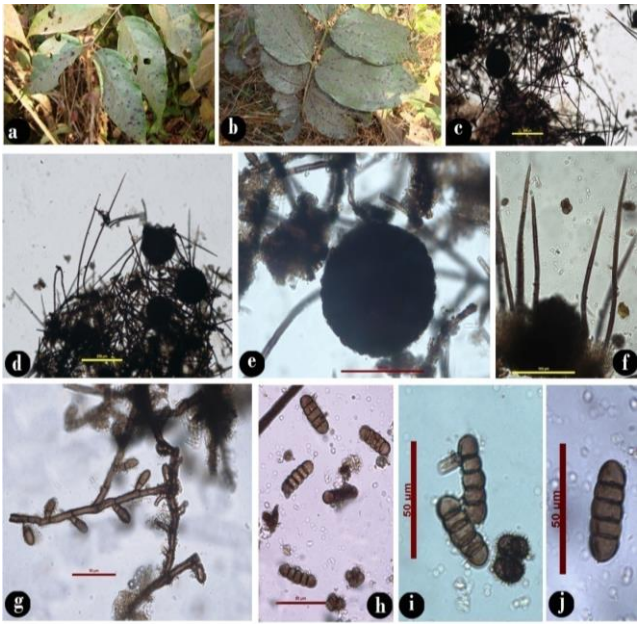


Figure 45. *Meliola jasminicola* (a) Black mildews of *Jasminum multiflorum* (b) Black mildews of *Strychnos nux-vomica* (c-d) Colonies (e) Perithecia (f) mycelia setae (g) Appresoria with phialides (h-j) Ascospores. [Scale bar: c, d = 200 µm; e, f = 100 µm; (g-j) = 50 µm.]

Meliola mangiferae *Earle, Bull. New York Bot. Gard. 3: 307 1905 [1904]. Figure 46*

Specimen examined: On the leaves of *Mangifera indica* L. (Anacardiaceae), On the way to Amboli Ghat, Sindhudurg Dist. Maharashtra, India, 22.01.2012, RD, 200219 BSI (WC).

Known distribution: On Leaves of *M. indica*, Karnataka, Kerala, South Andaman, Tamil Nadu (Hosagoudar 1996).

Remarks: This is the first record of the fungus in Maharashtra state.

Meliola melanoxylonis *Hosag. & C.M. Pillai, in Hosagoudar, Raghu & Pillai, Nova Hedwigia 58 (3-4): 540 1994. Figure 47*

Specimens examined: On the leaves of

Acacia auriculiformis Benth. (Leguminosae), Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200146 BSI (WC).

Carissa spinarum L. syn. *Carissa congesta* Wight, (Apocynaceae), Kirbet, Ratnagiri Maharashtra, India, 23.01.2013, RD, 200935 BSI (WC).

Known distribution: On leaves of *A. auriculiformis* from Karnataka (Maheshwari et al. 2012).

Remarks: This is the first record of the fungus in Maharashtra state, and also, *C. spinarum* forms a new host record for *M. melanoxylonis* from India.

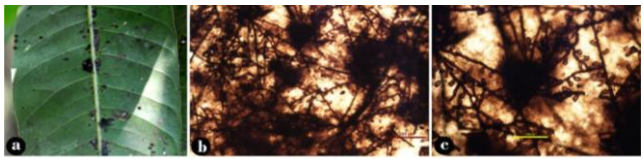


Figure 46. *Meliola mangiferae* (a) Black mildews of *Mangifera indica* (b-c) Colonies with perithecia, setae, appressoria, and phialides. [Scale bar: b = 200 µm; c = 100 µm.]

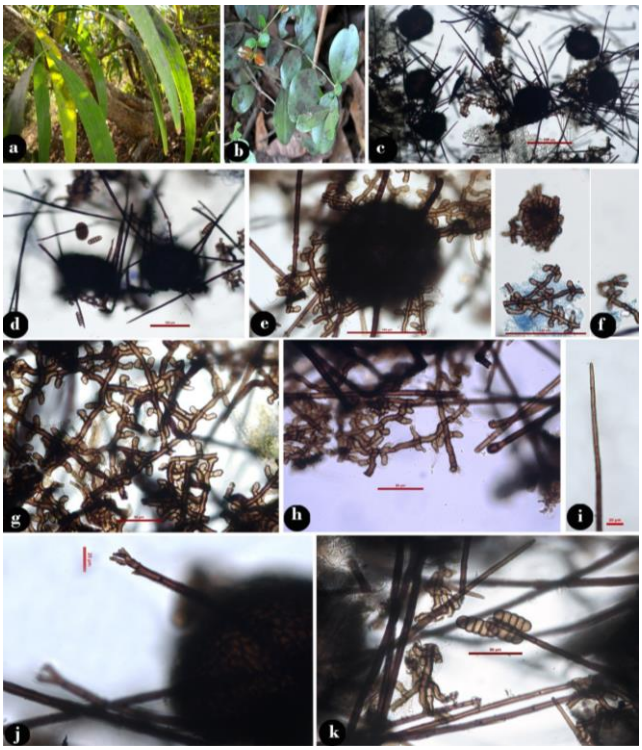


Figure 47. *Meliola melanoxylonis* (a) Black mildews of *Acacia auriculiformis* (a) Black mildews of *Carissa congesta* (c-d) Perithecia with mycelial setae (e) Perithecia and appressoria (f) Young perithecia and appressoria (g-h) Appresoria and phialides (i-j) Apical part of setae (k) Ascospores. [Scale bar: c = 200 µm; d, e = 100 µm; (f-h), k = 50 µm; i, j = 20 µm.]

Meliola memecyli *Syd. & P. Syd., Annls mycol. 15 (3/4): 189 1917. Figure 48*

Specimen examined: On the leaves of *Memecylon umbellatum* Burm.f. (Melastomataceae), Location 2, Dajipur WLS, Kolhapur District, Maharashtra, India, 09.02.2015, RD, 201646 BSI (WC).

Known distribution: On leaves of *M. umbellatum* from Karnataka, Kerala, and Maharashtra.

Meliola memecylicola *Hansf, Sydowia 10 (1-6): 78 1957. Figure 49*

Specimen examined: On the leaves of *Memecylon talbotianum* Brandis (Melastomataceae), Location 1, Radhanagri WLS, Maharashtra, India, 23.01.2012, RD, 200277 BSI (WC).

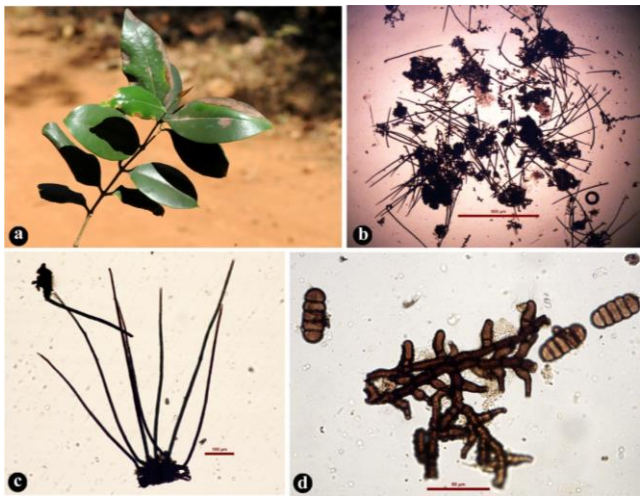


Figure 48. *Meliola memecyli* (a) Black mildew of *Memecylon umbellatum* (b) Colony (c) Mycelial setae (d) Ascospores. [Scale bar: b = 500 µm; c = 100 µm; d = 50 µm.]

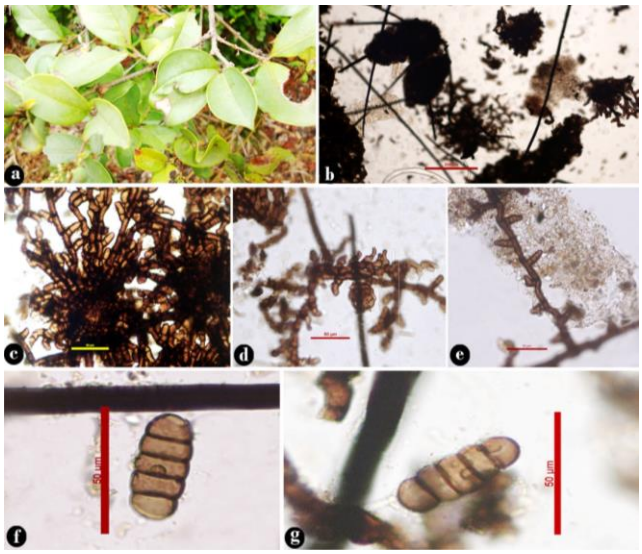


Figure 49. *Meliola memecylicola* (a) Black mildews of *Memecylon talbotianum* (b) Perithecia (c) appressoria (d-e) phialides (f-g) Ascospores. [Scale bar: b = 200 µm; c-g = 50 µm.]

Meliola mitragynae *Syd. & P. Syd., Philipp. J. Sci., C, Bot. 8 (5): 478 1913. Figure 50*

Specimen examined: On the leaves of *Mitragyna parvifolia* (Roxb.) Korth. (Rubiaceae), Sanjay Gandhi National Park, Maharashtra, India, 25.09.2013, RD, 196410 BSI (WC).

Known distribution: On living leaves of *M. parvifolia* from Karnataka and Uttar Pradesh (Hosagoudar 1996).

Remarks: This is a new record for Maharashtra state.

Meliola nothopegiae *Hansf. 1957 Figure 51*

Specimen examined: On the leaves of *Nothopegia* sp. (Anacardiaceae), Location 1, Dajipur WLS, Kolhapur District, Maharashtra, India, 09.02.2015, RD, 201606 BSI (WC).

Known distribution: Earlier reported on leaves of *Nothopegia* sp. from Mysore, Karnataka (Hansford 1956).

Remarks: This is the first report of the occurrence of fungus from Maharashtra.

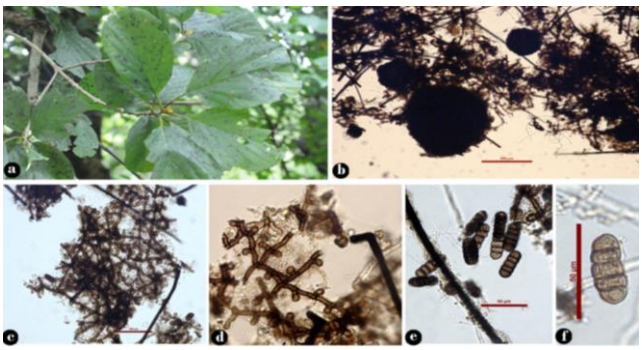


Figure 50. *Meliola mitragynae* (a) Black mildews of *Mitragyna parvifolia* (b) Perithecia (c-d) appresoria and phialides (e-f) ascospores. [Scale bar : b = 200 µm; c = 100 µm; e, f = 50 µm.]

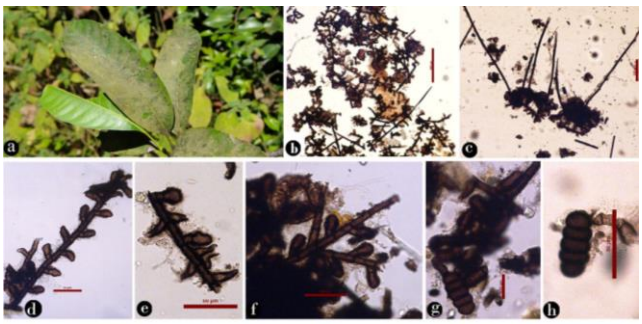


Figure 51. *Meliola nothopegiae* (a) Black mildews of *Nothopegiae* sp., (b) Colonies with perithecium, (c) Perithecium with mycelial setae, (d-f) Mycelia with appressoria & phialides, (g-h) Ascospores [Scale Bar: b, f = 200 µm; c, g = 100 µm; d, e, h = 50 µm.]

Meliola pandanacearum *Hosag. & T.K. Abraham, Indian Phytopath. 51 (3): 303 1999. Figure 52*

Specimen examined: On the leaves of Pandanus tectorius Parkinson ex Du Roi (Pandanaceae), Fanaswadi, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200140 BSI (WC).

Known distribution: On *Pandanus odoratissima*, TGBRI, Thiruvananthapuram, Kerla (Hosagoudar and Abraham 1997)

Remarks: This is a new record of the fungus for Maharashtra.

Meliola pongamiae *Hosag. & T.K. Abraham, Nova Hedwigia 68 (3-4): 483 1999. Figure 53*

Specimen examined: On the leaves of *Pongamia pinnata (*L.) Pierre (Leguminosae), Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200163 BSI (WC).

Known distribution: On *P. pinnata* from Kerala and Tamilnadu (Hosagoudar 2008).

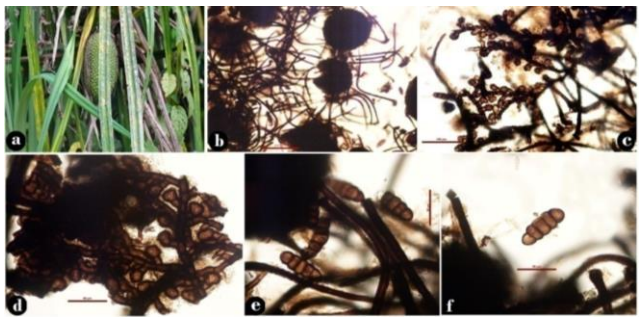


Figure 52. *Meliola pandanacearum* (a) Black mildews of *Pandanus tectorius* (b) Perithecia and mycelial setae (c-d) Mycelium with appressoria and phialides (e-f) Ascospores. [Scale bar: b = 200 µm; c = 100 µm; d-f = 50 µm.]

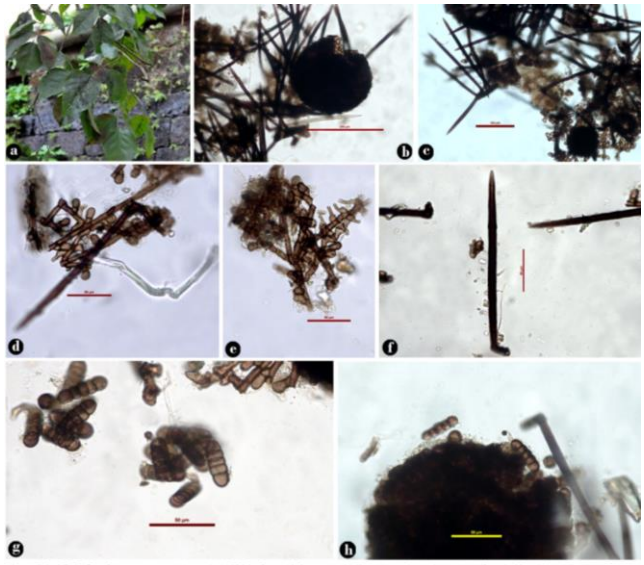


Figure 53. *Meliola pongamiae* (a) Black mildews of *Pongamia pinnata* (b-c) Perithecia and mycelia setae (d-e) Mycelium with appressoria and phialides (f) mycelial setae (g-h) Ascospores. [Scale bar : b = 200 µm; c = 100 µm; (d-h) = 50 µm.]

Meliola semecarpi-anacardii *Hosag., Kaver., Raghu & Goos, Mycotaxon 51: 114 1994. Figure 54*

Specimen examined: On the leaves of *Semecarpus anacardium* L.f. (Anacardiaceae), Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200158 BSI (WC).

Known distribution: It was reported on leaves of *S. anacardium* from Kerala, Karnataka, and Tamil Nadu (Bilgrami et al. 1991; Hosagoudar 1994).

Remarks: This is a new record of fungus for Maharashtra.

Meliola *sp. Figure 55*

Specimen examined: On leaves of *Casearia* sp. (Salicaceae), Location 1, Koyna WLS, Satara Dist.,

Maharashtra, India, 13.02.2015, RD, 201744 BSI (WC).

Remarks: Review of the literature reveals that no species of *Meliola* has been reported on *Caesaria* sp. Thus it forms a new host record from India.

Figure 54. *Meliola semecarpi-anacardii* (a) Black mildews of *Semecarpus anacardium* (b-c) Perithecia and mycelia setae (d-e) Mycelium with appressoria and phialides (f-g) Setae with ascospores (h) Ascospores. [Scale bar: b, c = 200 µm; (d-h) = 50 µm.]

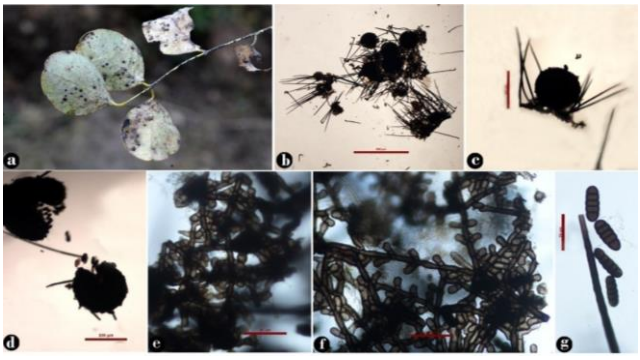


Figure 55. *Meliola* sp. (a) Black mildews of *Casearia* sp. (b-c) Perithecia and mycelia setae (d) Perithecium with ascospores (e-f) Mycelium with appressoria and phialides (g) Setae and ascospores. [Scale bar : b = 500 µm; c, d = 200 µm; (e-g) = 20 µm]

Meliola tylophorae *Hosag., in Hosagoudar & Goos, Mycotaxon 37: 250 1990. Figure 56*

Specimen examined: On the leaves of *Tylophora* sp. (Apocynaceae), Akeri, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200038 BSI (WC).

Known distribution: Earlier reported on leaves of *Tylophora indica* (Burm.f.) Merr. (Maheshwari et al. 2012) and on leaves of *Tylophora caparidifolia* Wight & Arn. from Kerala (Hosagoudar 1996).

Remarks: It is a new record of fungi for Maharashtra state.

Meliola tylophorae-indicae *Hosag. & Manoj k., Indian Phytopath. 57 (4): 466 2004. Figure 57*

Specimen examined: On the leaves of *T. indica* (Burm.f.) Merr. (Apocynaceae), Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200150 BSI (WC).

Known distribution: Earlier reported on leaves of *Tylophora indica* (Burm.fil.) Merr. from Kerala (Hosagoudar 2008).

Remarks: This is a new record of fungus for Maharashtra state.

Meliola unonicola *Hosag. & T.K. Abraham, Kavaka 24: 16 1997 [1996]. Figure 58*

Specimen examined: On the leaves of *Diospyros* sp., Phansad WLS, Raigad, 28.09.2013, RD, 196477 BSI (WC).

Remarks: This is a new host record from India.

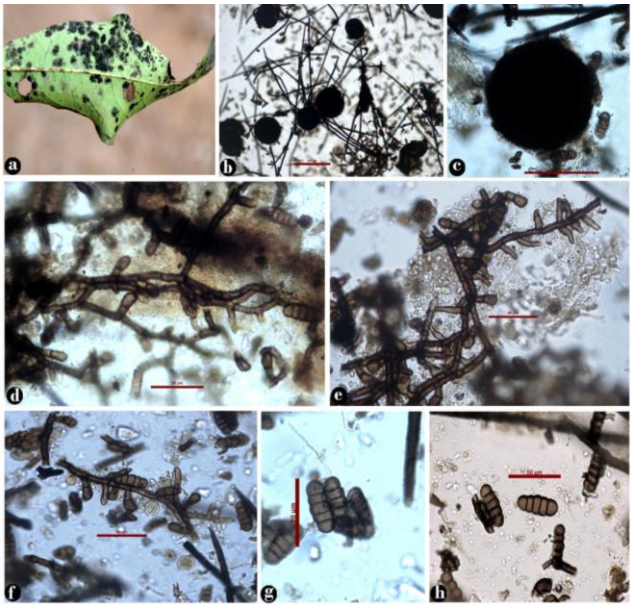


Figure 56. *Meliola tylophorae* (a) Black mildews of *Tylophora* sp. (b) Perithecia and mycelial setae (c) Perithecium (d-f) Mycelium with appressoria and phialides (g-h) Ascospores. [Scale bar: b = 200 µm; c = 100 µm; (d-h) = 50 µm.]

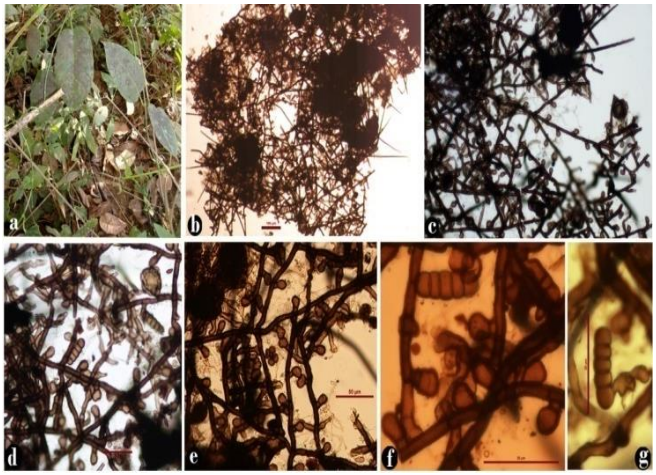


Figure 57. *Meliola tylophorae-indicae* (a) Black mildews of *Tylophora indica* (b-c) Colonies (d-e) Mycelial appressoria, phialides and ascospores (f-g) Ascospores. [Scale bar: b = 100 µm; (d-g) = 20 µm]

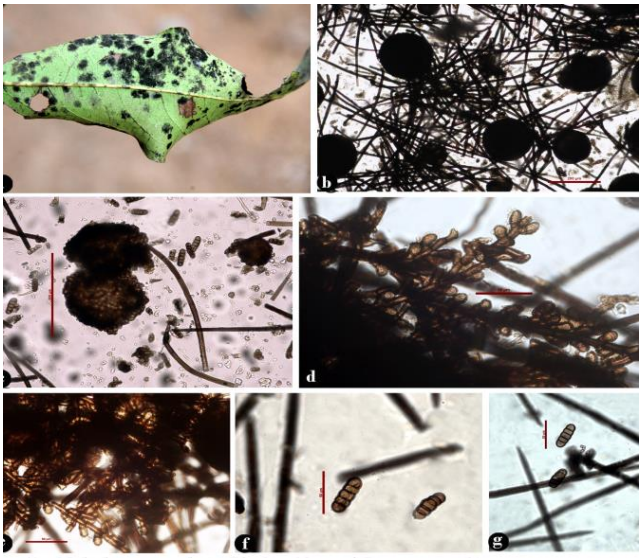


Figure 58. *Meliola unonicola* (a) Black mildews of *Diospyros* sp. (b) Perithecia and mycelia setae (c) Perithecium with ascospores (d-e) Mycelium with appressoria (f-g) Ascospores. [Scale bar: b, c = 200 µm; (d-g) = 50 µm]

Meliola ziziphi *Hansf. & Thirum., Farlowia 3 (3): 299 1948. Figure 59*

Specimen examined: On the leaves of *Ziziphus jujuba* Mill. (Rhamnaceae), Fanaswadi, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200139 BSI (WC).

Known distribution: Earlier reported on leaves of *Z. rugosa*, Karnataka (Hansford and Thirumalchar 1948), Maharashtra. (Thite and Kulkarni 1973); on leaves of *Ziziphus* sp., Coimbatore (Hosagoudar 1996); On *Z. jujuba*, on *Z. oenoplia*, *Z. rugosa* and *Z. rugosa*, Kerala (in Maheshwari et al. 2012).

Figure 59. *Meliola ziziphi* (a) Black mildews of *Ziziphus rugosa* (b) Perithecium (c-d) Mycelium with appresoria and phialides (e-g) Setae (h) Ascospores. [Scale bar: b, e = 200 µm; c, h = 50 µm; d, g = 20 µm, f = 100 µm]

Meliolina mollis *(Berk. & Broome) Höhn, Sber. Akad. Wiss. Wien, Math.-naturw. Kl., Abt. 1128: 557 1919. Figure 60*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes Incertae sedis, Incertae sedis, Meliolinaceae.

Specimens examined: On the leaves of –

Leea indica (Burm. f.) Merr. (Vitaceae), Guest House, Kesari, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200117 BSI (WC).

Memecylon umbellatum Burm.f. (Melastomataceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200089 BSI (WC);

Memecylon umbellatum Burm.f. (Melastomataceae), PWD Rest House, Mahabaleshwar, Satara Dist., Maharashtra, India, 24.01.2012, RD, 200289 BSI (WC);

Memecylon umbellatum Burm.f. (Melastomataceae), Old Mahabaleshwar, 24.01.2012, RD, 200329 BSI (WC).

Persicaria auriculata (Makino) Masam. Mahabaleshwar, Satara, Maharashtra, India, RD, 200314 BSI (WC).

Known distribution: On leaves of *Eugenia*, *Leptospermum*, and *Syzgium* (Burma, New Zealand, Srilanka, and India). It has been reported on leaves of *Syzygium montannum* from Nilgiris, Tamil Nadu (Pirozynski 1934); New Delhi (Ganju and Nair 1991); Coorg (Karnataka) and Silent Valley, Kerala (Hosaguadar 2008); Mahabaleshwar, Maharashtra (Anahosur 1969). There is a report of the occurrence of *M. memecylon* on the leaves of *M. umbellatum* Burm.f. (Melastomataceae) from Ambha ghat, Amboli ghat, Radhanagari, Petlon, Sangli, (Pandey 2008). A review of pertinent literature reveals that no species of *M. mollis* has not been reported on *M. umbellatum, L. indica,* and *P. auriculata.*

Remarks: This is a new host record from India.

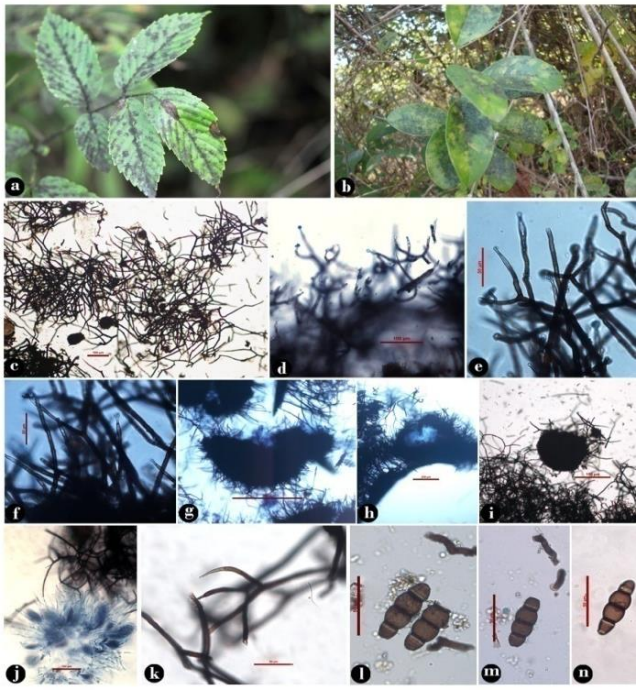


Figure 60. *Meliolina mollis* (a) Black mildews of *Leea indica* (b) Black mildews of *Memecylon umbellatum* (c) Colonies (d-f) Phialides and conidia (g-i) Pseudothecia covered with setae (j) Immature asci (k) Apical part of setae (i-n) Ascospores. [Scale Bar: c, f = 100 µm; d = 200 µm; (g-j) = 50 µm]

Mitteriella ziziphina *Syd., Annls mycol. 31(1/2): 95 1933. Figure 61*

Fungi, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Englerulaceae

Specimen examined: On the leaves of *Z. jujuba* Mill. (Rhamnaceae), Shikur, Thane Dist. Maharashtra, India, 16.10.2012, RD, 201036 BSI (WC).

Known distribution: Reported on leaves of *Z. Jujuba* from Uttar Pradesh. (Tandon 1935); *Z. nummularia*, Rajasthan (Berkeley 1882); *Ziziphus* sp., New Delhi (Agarwal and Sarbhoy 1979); *Ziziphus xylopyra* Jabalpur, Madhya Pradesh: (Sahni 1964); *Z. rotundifolia*, Majhgawan, UP (Sydow and Mitter 1933); *Z. oenoplia* and *Z. jujuba*, UP (Tandon 1935).

Remarks: This is a new record of the fungus in Maharashtra state.

Pirozynskiella solanina *(Sacc. & P. Syd.) S. Hughes, Mycologia 99(4): 632 2007. Figure 62*
=Helminthosporium solaninum *Sacc. & P. Syd. [as 'Helmisporium'], in Saccardo*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Pleosporomycetidae, Pleosporales, Massarinaceae.

Specimen examined: On the leaves of *J. multiflorum* (Oleaceae), Kudal, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, 200080 BSI (WC).

Notes: *Pirozynskiella*, typified by *P. solaninum* comb. nov. (Sacc. & P. Syd.) S. Hughes has an obligate association with asterinaceous fungi. However, only two species of fungus have been reported worldwide. Remarks: This is the first record of the fungus from India.

Prillieuxina polyalthiae *Hosag. & T.K. Abraham, Indian Phytopath. 51(4):391 1999. Figure 63*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Dothideomycetidae, Asterinales, Asterinaceae.

Specimen examined: On living leaves of *Desmodium* sp. (Leguminosae), Akeri, Sawantwadi, Sindhudurg Dist., Maharashtra, India, 20.01.2012, RD, BSI (WC) 200041.

Known distribution: On living leaves of *Polyalthia longifolia* (Sonn.) Thwaites (Annonaceae) from Kerala (Hosagoudar and Abraham 1998).

Remarks: This is a new record of fungus from Maharashtra's forest and a new record of *Desmodium* sp.

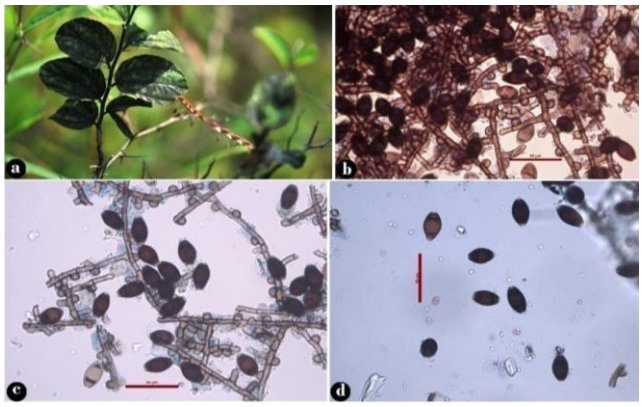


Figure 61. *Mitteriella ziziphina* (a) Black mildews of *Ziziphus jujube* (b-c) Mycelia, appresoria, phialides and ascospores (d) ascospores. [Scale bar: b-d = 50 µm]

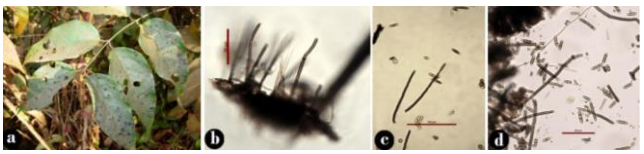


Figure 62. *Pirozynskiella solanina* (a) Infected leaves of *Jasminum multiflorum* (b) Conidiophores (c-d) Conidiophores and conidia. [Scale bar : b, d = 50 µm; c = 100 µm]

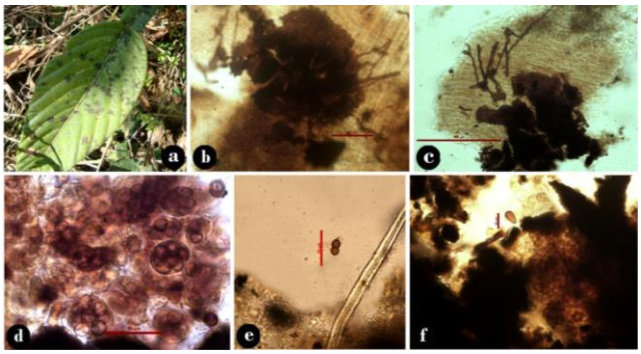


Figure 63. *Prillieuxina polyalthiae* (a) Black mildews of *Desmodium* sp. (b-c) Thyriothecia (d) Asci (e) Aspcospores (f) Pycniothyriospore. [Scale bar : b, c = 100 µm; d, e = 50 µm; f = 20 µm]

Questieriella strychni *Hosag., J. Econ. Taxon. Bot. 28(1): 196 2004. Figure 64*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Englerulaceae.

Specimen examined: On the leaves of *P. pinnata* (Leguminosae), Kesari, Sawantwadi Tal., Sindhudurg Dist., Maharashtra, India, 21.01.2012, RD, 200163 BSI (WC).

Known distribution: Kerala, Karnataka (Bilgrami et al. 1991; Maheshwari et al. 2012).

Notes: Worldwide, 19 species of *Questieriella* have been reported.

Remarks: This is the first record of the fungus from the forests of Maharashtra, India.

Sarcinella cassiae-fistulae *Hosag. & Shajivaz in Hosagoudar, Zoos' Print Journal 17 (12): 947 2002. Figure 65*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Englerulaceae.

Specimen examined: On the leaves of *Cassia fistula* L. (Leguminosae), on the way to Dahanu, Thane Dist., Maharashtra, India, 17.10.2012, RD, 201065 BSI (WC).

Notes: *S. cassiae* Munjal and Kapoor (1963) is known as *Cassia tora* and *C. occidentalis* from Belgaum, Karnataka, and Bhimtal, Kumaon. However, *S. cassiae-fistulae* differs from it in having thin hypophyllous colonies, having only sarciniform and smaller conidia

Remarks: This is a new record of the species from Maharashtra.

Sarcinella crytolepidae *Pande, M.V.M. Patrika 13: 1, 1978. Figure 66*

Specimen examined: On living leaves of *Cryptolepis buchanani* (Apocynaceae), East Melghat Tiger Reserve, Amravati Dist., Maharashtra, India, 16.01.2014, RD, 197086 BSI (WC).

Known distribution: India, Maharashtra, India, Poona, on leaves of *C. buchanani* (Periplocaceae) (Pande 1978).

Remarks: This is the second report of the occurrence of fungus from Maharashtra.

Sarcinella cryptostegiae *(Singh, 1993). Figure 67*

Specimen examined: On the leaves of a *Cryptostegia* sp. (Periplocaceae), Malshej Hills, Pune Dist., Maharashtra, India, 20.10.2012, RD, 201193 BSI (WC).

Remarks: This is a new record of the species from Maharashtra.

Sarcinella diospyri *R.C. Rajak & Soni, Indian J. Mycol. Plant Path. 11 (1): 89 1981. Figure 68*

Specimen examined: On living leaves of *Diospyros* sp (Ebenaceae), Pench TR, (Part of Nagpur Dist.), Maharashtra, India, 13.01.2014, RD, 197021 BSI (WC).

Known distribution: Amarkantak, (MP); Gorakpur (UP).

Remarks: This is a new record of the species from Maharashtra.

Figure 64. *Questieriella strychni* (a) Black midews of *Pongamia pinnata* (b-c) Mycelia with appresoria (d-e) Questieriella type of conidia. [Scale bar : (b-e) = 50 µm]

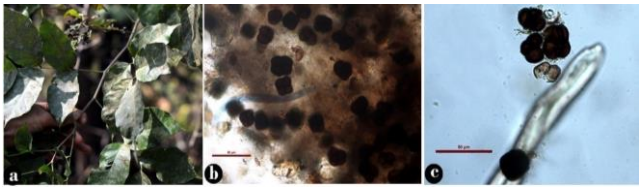


Figure 65. *Sarcinella cassiae-fistulae* (a) Black mildews of *Cassia fistula* (b-d) Hyphae, appresoria and conidia. [Scale bar : (b-d) = 50 µm]

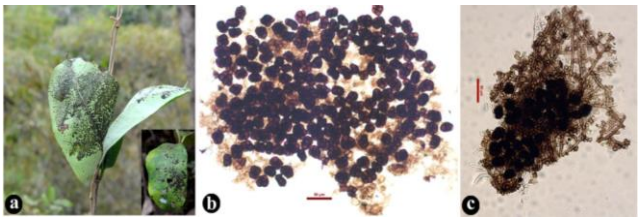


Figure 66. *Sarcinella crytolepidae* (a) Black mildews of *Cryptolepis buchanani* (b-c) Hyphae, appresoria and sarciniform conidia. [Scale bar : b, c = 50 µm]

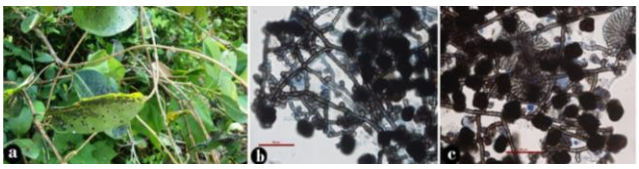


Figure 67. *Sarcinella cryptostegiae* (a) Black mildews of *Cryptostegia* sp. (b) Hyphae, appressoria, conidiophores, and conidia (c) Sarciniform conidia with colonies of *Schiffnerula* sp. [Scale bar: b, c = 50 µm]

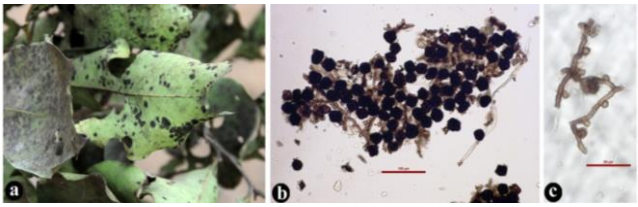


Figure 68. *Sarcinella diospyri* (a) Black mildews of *Diospyros* sp. (b) Hyphae, appressoria and sarciniform conidia (c) Appressoria [Scale bar: b = 100 µm; c = 50 µm]

Sarcinella gmelinae *Hosag. Archana, Harish, Riju & D.K. Agarwal, Indian Phytopath. 61 (2): 247 2008. Figure 69*

Specimen examined: On the leaves of *Tectona grandis* L.f. (Lamiaceae), Pulachiwadi, Thane Dist., Maharashtra, India, 18.10.2012, RD, 201119 BSI (WC).

Known distribution: on leaves of *Gmelina arborea* Roxb. ex Sm. from Kerala, India.

Remarks: This is a new record of the fungus from Maharashtra.

Sarcinella gymnosporiae *Subhedar & Rao ex Hosag. in Hosagoudar, Zoos' Print Journal 17 (8): 837 2002. Figure 70*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Englerulaceae.

Specimen examined: On the leaves of undetermined plant sp.-10, on the way to Dahanu, Thane Dist., Maharashtra, India, 17.10.2012, RD, 201099 BSI (WC).

Known distribution: on leaves of *Gymnosporia rothiana* M.A. Lawson Maharashtra, Pune (Rao 1968).

Sarcinella loranthacearum *Hosag., Jac. Thomas & D.K. Agarwal J. Yeast Fungal Res. 2 (5): 85 2011. Figure 71*

Specimen examined: On the leaves of *Firmiana colorata* (Roxb.) R.Br. (Malvaceae), Suryamal, Thane Dist., Maharashtra, India, 16.10.2012, RD, 201149 BSI (WC).

Remarks: No species of *Sarcinella* have been reported on *F. colorata*. Thus it is a new record of the association of *S. loranthacearum* with *F. colorata*.

Sarcinella *sp. Figure 72*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Englerulaceae.

Specimen examined: On living leaves of *Elaeagnus conferta* L. (Elaeagnaceae) Location 2, Chandoli National Park, Satatra Dist., Maharashtra, India, 12.02.2015, RD, 201723 BSI (WC).

Remarks: No species of *Sarcinella* have been reported on *E. conferta*. Thus it is the first report of the occurrence of *Sarcinella* on *E. conferta*.

Schiffnerula celastri *Hosag., Riju & Sabeena, in Hosagoudar, Riju & Sabeena, Indian Journal of Science and Technology 1(3): 1 2008. Figure 73*

Fungi, Ascomycota, Pezizomycotina, Dothideomycetes, Incertae sedis, Incertae sedis, Englerulaceae.

Specimen examined: On the leaves of *Celastrus paniculatus* Willd. (Celastraceae), Toranmal WLS, Nandurbar Dist., Maharashtra, India, 21.09.2014, RD, 196648 BSI (WC).

Known distribution: Munnar, Wayanad, Padinjarethara (Kerala); Katarnia Ghat (Uttar Pradesh); Pateghar **(**Maharashtra**)**; Kodagu (Karnataka) (Bigrami et al. 1991; Maheshwari et al. 2012).

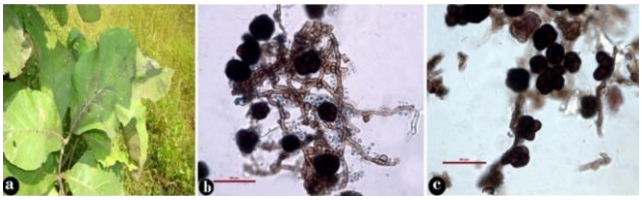


Figure 69. *Sarcinella gmelinae* (a) Black mildews of *Tectona grandis* (b-c) Hyphae, appressoria, conidiophores, and conidia. [Scale bar: b, c = 50 µm]

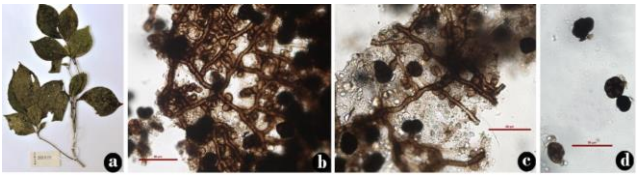


Figure 70. *Sarcinella gymnosporiae* (a) Black mildews of unidentified plant (b-c) Hyphae, appressoria, conidiophores, and conidia (d) Conidia. [Scale bar : (b-d) = 50 µm]

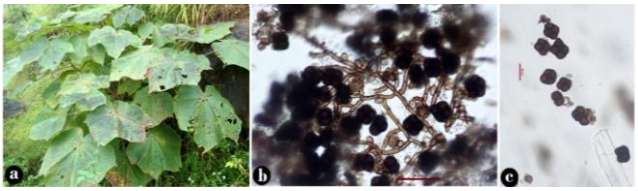


Figure 71. *Sarcinella loranthacearum* (a) Black mildews of *Firmiana colorata* (b) Hyphae, appressoria, conidiophores, and conidia (c) Conidia. [Scale bar: b = 50 µm; c = 25 µm]

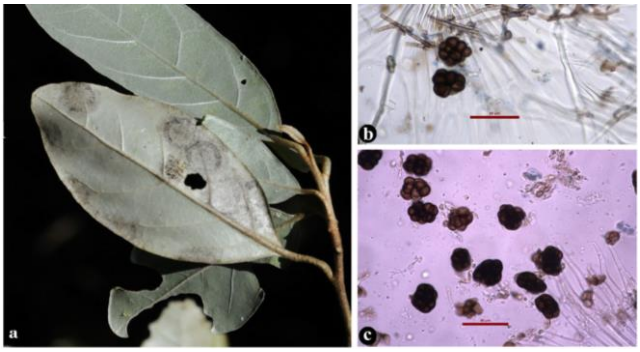


Figure 72. *Sarcinella* sp. (a) Sooty mold on *Elaeagnus conferta* (b) Hyphae, appresoria and conidia (c) Conidia. [Scale bar: b, c = 50 µm]

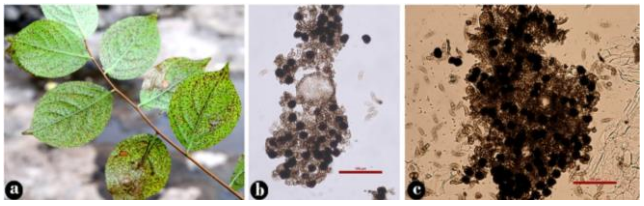


Figure 73. *Schiffnerula celastri* (a) Black mildews of *Celastrus paniculatus* (b) Colonies having appressoria, conidiophores, thyriothecia, and sarcinellate conidia (c) Questieriella conidia and sarcinellate conidia. [Scale bar: b, c = 100 µm]

Statistical results

As shown in Figure 2 (A), *Meliola* (Fam. Meliolaceae) was the dominant genus with 35 species, followed by *Asterina* (12) fam. Asterinaceae and *Sarcinella* (8) Fam. Englerulaceae. As Figure 74 A shows, *M. mollis* was the dominant taxon, identified from a maximum of 5 collections, 633 followed by *Sarcinella* sp. (4), *Meliola eugeniae-stocksii* (3), *Meliola ixorae* var. *macrospora* (3). Diversity measures (Table 2) were calculated by combining species richness with evenness (Table 2). Gini-Simpson's Index was 0.9818, and Shannon's Index was 4.1668. Pielou's evenness index was 0.9743, while true diversity, calculated as an effective number of species was 66, less than observed species richness (74).

Discussion

The present paper examines the diversity of Maharashtra's black mildews from taxonomic and ecological perspectives. Some areas of Maharashtra are well explored concerning documentation of black mildew fungi. E.g., Bhise et al. (2015) reported 46 new records for the state of Maharashtra from Mahabaleshwar alone. However, most of the work on black mildew is reported from the Western Ghats region of Kerala, Tamil Nadu, and Karnataka states (Bhise et al. 2015).

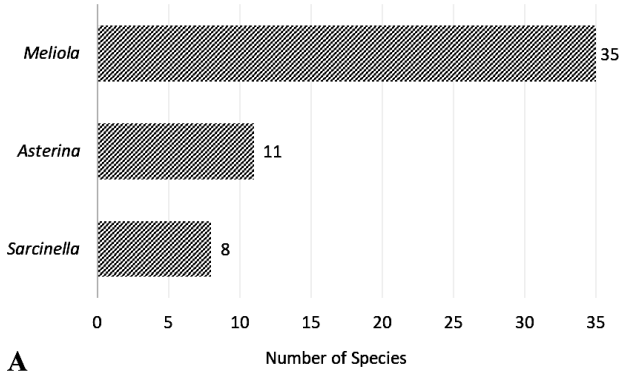
Therefore, there was a need to document the black mildew of Maharashtra. Consequently, greater emphasis was laid on extensive geographical coverage during the field surveys. All the major forest types within the state of Maharashtra were visited, with special emphasis on densely forested areas of Western Maharashtra (which included biodiversity hotspots of Western Ghats) and tiger reserves and protected areas of Northern Maharashtra. The present study is also unique in incorporating the ecological dimensions of black mildew. A total of 72 species under 14 genera were identified from 87 collections. The authors earlier published some fungi documented in Table 2. However, the focus and scope of those publications were entirely different, viz., on the percentage distribution of disease symptoms (Dubey and Pandey 2017) and enumeration and ecology of foliicolous fungal taxa (Dubey and Pandey 2019, 2022a, b).

Further detailed studies on Maharashtra's black mildew fungi revealed some of these fungi as new records to India, new records to Maharashtra state, and new host records to India, which is mainly highlighted in the present work. The present study on black mildew fungi of Maharashtra state of India resulted in three new records of fungi to India, 31 new host records to India, 40 new records of fungi to the Maharashtra state of India, and one var. nov. viz., *A. jasmini* Hansf. var. *koyani* var.nov., depicted by checklist and Figures. It was admitted that among the myriads of fungi, *Meliola* was the most dominating genus and was represented by 35 species, while *M. mollis* was the dominant taxon, identified from a maximum of five collections. More than 90% of black mildew species reported in the present work are collected from the Western Ghats districts of Maharashtra. Besides taxonomy, we also calculated diversity measures to shed light on the ecological aspects of the black mildew fungi. The study area is highly diverse, as evidenced by high values of Gini-Simpson's Index (= 0.9818) and Shannon's Index (= 4.1668). A high value of Pielou's evenness index (*J'*= 0.9743) shows high equitability in species distribution. Moreover, to correct observed species richness for observed evenness, a measure of an effective number of species was calculated from Shannon's Index on examination of true diversity. True diversity or an effective number of species for the study area (64) is less than species richness or observed number of species (72) due to the absence of a perfectly equitable distribution of species ($J' \neq 1$).

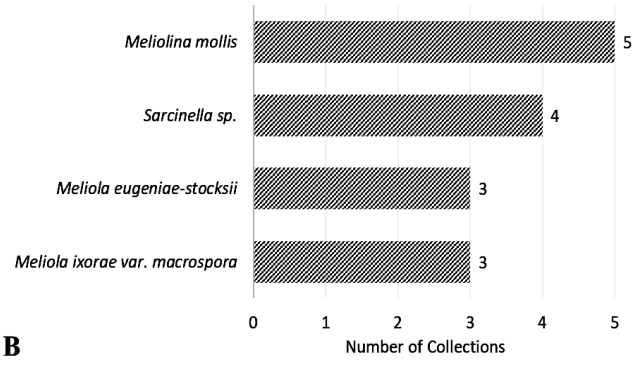
The present study thus provides important insights into the taxonomy, distribution, and ecology of black mildews of Maharashtra. However, the study also suggests the need for more intensive studies at a smaller geographical scale, such as a protected area or a district, as immense diversity is yet to be explored, which can not be captured in more geographically extensive studies.

Table 2. Diversity measures

Species Richness = Observed number of species	72
Simpson's Index (*D*)	0.0182
Gini Simpson's Index (*1-D*)	0.9818
Shannon's Index (*H*)	4.1668
Pielou's evenness index (*J'*)	0.9743
True Diversity= Effective number of Species (ENS_H)= e^H	64



A



B

Figure 74. Dominant taxa. A. Fungal genera with the highest number of species. B Fungal taxa obtained from the highest number of collections

Table 1. Documentation of new records /new host records of black mildew fungi

Name of Fungi	Family	Host plant	Collection no.	Location in the state of Maharashtra, India	Date	New record for India	New record to Maharashtra State	New host record to India
Amazonia elaeocarpi	Meliolaceae	*Leea indica*	200117	Kesari, Sindhudurg	21.01.2012		New record of fungus in Maharashtra	New Host record from India
Amazonia syzygii	Meliolaceae	*Syzygium cumini*	201751	Location 1, Metindoli, Koyna WLS, Satara Dist.	13.02.2015		New record of fungus in Maharashtra	
Asteridiella depokensis	Meliolaceae	*Vitex negundo*	200081	Kudal, Sawantwadi, Sindhudurg Dist.	21.01.2012		New record of fungus in Maharashtra	New Host record from India
Asterina capparis	Asterinaceae	*Capparis* sp.	200224	Amboli Ghat, Sindhudurg Dist.	22.01.2012		New record of fungus in Maharashtra	New Host record from India
Asterina delicatula	Asterinaceae	*Jasminum* sp.	200075	Sawantwadi, Sindhudurg	20.01.2012		New record of fungus in Maharashtra	New Host record from India
Asterina henianii	Asterinaceae	*Syzygium cumini*	201642	Location 1,Dajipur WLS, Kolhapur	09.02.2015		New record of fungus in Maharashtra	
Asterina hydrocotyles	Asterinaceae	*Lawsonia inermis*	196234	Junnar Forest, Pune Dist.	21.09.2013		New record of fungus in Maharashtra	New Host record from India
Asterina jasmini Hansf. var. *koyani* var.nov.	Asterinaceae	*Jasminum malabaricum*	201731	Chandoli NP, Sangli Dist.	12.02.2015	New variety		
Asterina jasminicola	Asterinaceae	*Jasminum multiflorum*	200080	Kudal, Sawantwadi, Sindhudurg Dist.	21.01.2012		New record of fungus in Maharashtra	
Asterina wrightiae	Asterinaceae	*Lagerstroemia* sp.	199560	Khandala, Pune Dist.	26.09.2011			New Host record from India
Asterina wrightii	Asterinaceae	*Paramignya monophylla*	194051	Forest Range, Dapoli, Ratnagiri	26.01.2013			New Host record from India
Balladyna pavettae	Balladynaceae	*Pavetta crassicaulis*	200326	Mahabaleshwar, Satara Dist.	24.01.2012	New record of the fungal species in India		New Host record from India
Balladyna pavettae	Balladynaceae	*Synedrella nodiflora*	200026	Akeri, Sawantwadi , Sindhudurg	20.01.2012			New Host record from India
Balladyna ugandensis	Parodiopsidaceae	*Pavetta* sp.	199628	Teragaon, Bhimashankar WLS, Pune Dist.	28.09.2011			New Host record from India
Balladyna vanderystii	Parodiopsidaceae	*Catunaregam spinosa*	200993	Kodawali, Bhimashankar WLS, Pune Dist.	29.09.2011		New record of fungus in Maharashtra	New Host record from India
Balladyna velutina	Parodiopsidaceae	*Pavetta indica*	196268	HarishchandragadWLS, Ahmednagar	21.09.2013	New record of the fungal species in India		
Meliola agrostistachydis	Meliolaceae	*Agrostistachys* sp.	201745	Location 1, Metindoli, Koyna WLS, Satara Dist.	13.02.2015		New record of fungus in Maharashtra	
Meliola allophyli-serrulati	Meliolaceae	*Allophylus* sp.	200143	Fanaswadi, Sawantwadi , Sindhudurg Dist.	21.01.2012		New record of fungus in Maharashtra	

Meliola alstoniae	Meliolaceae	Unidentified plant sp. 8	200157	Kesari, Sawantwadi Sindhudurg Dist.	21.01.2012	New record of fungus in Maharashtra	
Meliola buteae	Meliolaceae	*Butea monosperma*	196384	Sanjay gandhi NP, Mumbai	25.09.2013	New record of fungus in Maharashtra	
Meliola carissae	Meliolaceae	*Carissa spinarum*	201027	On the way to Jhap, Thane Dist.	16.10.2012	New record of fungus in Maharashtra	
Meliola desmodii-triquetri	Meliolaceae	*Desmodium triflorum*	200010	Akeri, Sawantwadi (Sindhudurg)	20.01.2012	New record of fungus in Maharashtra	
Meliola diospyri	Meliolaceae	*Diospyros* sp.	201629	Location 1, Dajipur WLS, Kolhapur Dist.	09.02.2015	New record of fungus in Maharashtra	
Meliola eugeniae-jamboloidis	Meliolaceae	*Carissa spinarum*	200084	Kudal, Sawantwadi Sindhudurg Dist.	21.01.2012	New record of fungus in Maharashtra	
Meliola eugeniae-stocksii	Meliolaceae	*Ficus* sp.	201782	Radhanagari WLS	10.02.2015		New Host record from India
Meliola eugeniae-stocksii	Meliolaceae	*Ixora brachiata*	200178	Amboli Ghat, Sindhudurg Dist.	22.01.2012	New record of fungus in Maharashtra	New Host record from India
Meliola eugeniae-stocksii	Meliolaceae	*Ixora brachiata*	200130	Fanaswadi, Sawantwadi	21.01.2012		New Host record from India
Meliola flemingiicola	Meliolaceae	*Lagerstroemia* sp.	200371	Pasarni Ghat, Satara Dist.	25.01.2012	New record of fungus in Maharashtra	New Host record from India
Meliola garhwalensis	Meliolaceae	*Jasminum malabaricum*	200335	Old Mahabaleshwar	24.01.2012	New record of fungus in Maharashtra	New Host record from India
Meliola holarrhenae	Meliolaceae	*Holarrhena pubescens*	196402	Sanjay Gandhi NP	25.09.2013	New record of fungus in Maharashtra	
Meliola holigarnae	Meliolaceae	*Holigarna* sp.	201754	Location 1, Metindoli, Koyna WLS, Satara Dist., Maharashtra	13.02.2015	New record of fungus in Maharashtra	
Meliola hyptidis	Meliolaceae	*Plectranthus* sp.	196393	Sanjay Gandhi NP, Mumbai	25.09.2013		New Host record from India
Meliola hyptidis	Meliolaceae	*Volkameria inermis* syn. *Clerodendrum inerme*	200085	Kudal, Sawantwadi, Sindhudurg Dist.	21.01.2012		New Host record from India
Meliola ixorae Yates var. *macrospora*	Meliolaceae	*Ixora brachiata*	200215	Location 1, Amboli Ghat, Sindhudurg Dist.	22.01.2012		New Host record from India
Meliola ixorae Yates var. *macrospora*	Meliolaceae	*Ixora brachiata*	200180	Location 2, Amboli Ghat, Sindhudurg Dist.	22.01.2012		New Host record from India
Meliola ixorae-coccineae	Meliolaceae	*Ixora brachiata*	200180	Amboli Ghat	22.01.2012		New Host record from India
Meliola jasminicola	Meliolaceae	*Jasminum multiflorum*	200080	Kudal, Sawantwadi, ,Sindhudurg Dist.	21.01.2012	New record of fungus in Maharashtra	New Host record from India
Meliola jasminicola	Meliolaceae	*Strychnos nux-vomica*	200083	Chillara, Sawantwadi , Sindhudurg	21.01.2012		New Host record from India
Meliola mangiferae	Meliolaceae	*Mangifera indica*	200219	On the way to Vengrula, Amboli Ghat	22.01.2012	New record of fungus in Maharashtra	
Meliola melanoxylonis	Meliolaceae	*Carissa spinarum*	200935	Kirbet, Ratnagiri	23.01.2013		New Host record from India

Meliola mitragynae	Meliolaceae	*Mitragyna parvifolia*	196410	Sanjay Gandhi NP, Mumbai	25.09.2013		New record of fungus in Maharashtra	
Meliola nothopegiae	Meliolaceae	*Nothopegia* sp.	201606	Location 1, Dajipur WLS, Kolhapur District,	09.02.2015		New record of fungus in Maharashtra	
Meliola pandanacearum	Meliolaceae	*Pandanus tectorius*	200140	Fanaswadi, Sawantwadi (Sindhudurg)	21.01.2012		New record of fungus in Maharashtra	
Meliola pongamiae	Meliolaceae	*Pongamia pinnata*	200163	Kesari, Sawantwadi, Sindhudurg	21.01.2012		New record of fungus in Maharashtra	
Meliola semecarpi-anacardii	Meliolaceae	*Semecarpus anacardium*	200158	Kesari, Sawantwadi, Sindhudurg	21.01.2012		New record of fungus in Maharashtra	
Meliola tylophorae	Meliolaceae	*Tylophora* sp.	200038	Akeri, Sawantwadi , Sindhudurg	20.01.2012		New record of fungus in Maharashtra	
Meliola tylophorae-indicae	Meliolaceae	*Tylophora indica*	200150	Kesari, Sawantwadi, Sindhudurg	21.01.2012		New record of fungus in Maharashtra	
Meliola unonicola	Meliolaceae	*Diospyros* sp.	196477	Phansad WLS Raigad Dist.	28.09.2013		New record of fungus in Maharashtra	New Host record from India
Meliolina mollis	Meliolaceae	*Leea indica*	200117	Kesari, Sawantwadi (Sindhudurg)	21.01.2012			New Host record from India
Meliolina mollis	Meliolaceae	*Memecylon umbellatum*	200289	PWD Rest House,Mahabaleshwar	24.01.2012			New Host record from India
Meliolina mollis	Meliolaceae	*Persicaria auriculata*	200314	Old Mahabaleshwar	24.01.2012			New Host record from India
Mitteriella ziziphina	Englerulaceae	*Ziziphus jujuba*	201036	Shikur, Thane Dist.	16.10.2012		New record of fungus in Maharashtra	
Pirozynskiella solanina	Massarinaceae	*Jasminum multiflorum*	200080	Kudal, Sawantwadi, Sindhudurg Dist.	21.1.2012	New record of the fungal species in India		
Prillieuxina polyalthiae	Asterinaceae	*Desmodium* sp.	200041	Akeri, Sawantwadi, Sindhudurg Dist.	20.1.2012		New record of fungus in Maharashtra	New Host record from India
Questieriella strychni	Englerulaceae	*Pongamia pinnata*	200163	Kesari, Sawantwadi Sindhudurg Dist	21.01.2012		New record of fungus in Maharashtra	
Sarcinella cassiae-fistulae	Englerulaceae	*Cassia fistula*	201065	On the way to Dahanu, Dahanu, Thane Dist.	17.10.2012		New record of fungus in Maharashtra	
Sarcinella cryptostegiae	Englerulaceae	*Cryptostegia* sp.	201193	Malshej Hills, Pune	20.10.2012		New record of fungus in Maharashtra	
Sarcinella diospyri	Englerulaceae	*Diospyros* sp.	197021	Pench TR, Nagpur	13.01.2014		New record of fungus in Maharashtra	
Sarcinella gmelinae	Englerulaceae	*Tectona grandis*	201119	Pulachiwadi, Thane Dist.	18.10.2012		New record of fungus in Maharashtra	
Sarcinella loranthacearum	Englerulaceae	*Firmiana colorata*	201149	Suryamal, Thane Dist.	16.10.2012			New Host record from India
Sarcinella sp.	Englerulaceae	*Elaeagnus conferta*	201723	Location 2, Chandoli NP, Satara Dist.	12.02.2015			New Host record from India
Schiffnerula celastri	Englerulaceae	*Celastrus paniculatus*	196648	Nandurbar	21.09.2014		New record of fungus in Maharashtra	

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Biomass and carbon accumulation in Northern Bangladesh *Eucalyptus* plantations: Effects of stand structure and age

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Abstract. *Dey T, Islam MDA, Jubair SMR. 2022. Biomass and carbon accumulation in Northern Bangladesh* Eucalyptus *plantations: Effects of stand structure and age. Asian J For 6: 126-132. Eucalyptus* plantations are a significant carbon sink as a fast-growing species in Bangladesh, but little is known regarding biomass, carbon output, and dynamics with stand age. We, therefore, assessed the stand structure, biomass accumulation, carbon storage, and their changing patterns with age in *Eucalyptus camaldulensis* Dehnh. plantations in the northern part of Bangladesh in early 2021. Biomass and carbon stocks were estimated using the allometric models specific for *E. camaldulensis* from the biophysical tree parameters (i.e., height and DBH). We used the data from 45 sample plots (100 sq. m each) covering different age classes such as 2, 5, 7, 8, 11, 13, and 21 years. The aboveground, belowground, total biomass, and carbon significantly varied between stand ages ($p<0.05$). The highest aboveground, belowground, and total carbon stocks were observed at 21 years, and the lowest was found at two years. We observed a positive and strong relationship between total carbon and stand variables such as stand height, diameter at breast height, basal area, crown width, crown length, and bole height but a negative relationship with density. The mean annual increment of both biomass and carbon increased sharply up to seven years and then decreased. Despite having some ecological constraints, *E. camaldulensis* accumulate a large amount of carbon from the atmosphere, perhaps aiding climate change mitigation.

Keywords: Age, biomass, carbon accumulation, *Eucalyptus camaldulensis*, and stands structure

INTRODUCTION

Carbon dioxide (CO_2) levels in the atmosphere are assumed to have played a substantial role in climate change and come from power generation (38%), transportation (26.56%), building (8.07%), industries (24.76%), and agriculture (1.81%) (Canadell et al. 2007; Yoro and Daramola 2020). The essential strategy for combating climate change is to reduce CO_2 and emissions of other greenhouse gas (IPCC 2001). Through vegetation, forests help mitigate the greenhouse impact by absorbing CO_2 from the atmosphere (Du et al. 2015; Wirabuana et al. 2021). As trees are good carbon sequesters, planted forests (plantations) are regarded as a mitigating tool against the expected rise in atmospheric carbon dioxide concentrations (Sands et al. 1999; Kurz et al. 2009). Also, reduce the impact of natural forest exploitation (negative impacts) (Evans and Turnbull 2004; Kaul et al. 2010; Payn et al. 2015).

In the tropics and subtropics, plantation forestry has focused on a small number of colonizing species with a rapid growth rate, such as *Acacia*, *Eucalyptus*, *Gmelina*, *Pinus*, *Tectona*, and *Populus* (Evans 1992; Harwood and Nambiar 2014). Among these, *Eucalyptus* is well-known for its quick growth, socio-economic and medicinal value, and value as a cash crop due to the availability of wood, particularly for timber and biomass fuel (Dessie and Erkossa 2011; Khan et al. 2020). *Eucalyptus camaldulensis* Dehnh is one of the most common tree species in the village zone of Bangladesh (MoEFCC 2018), meeting a critical demand for residential fuelwood, poles, and posts (Ahmed and Akhter 1995). Plantations in tropical and temperate climates contain significant carbon reserves (Malhi et al. 2008), and fast-growing forest plantations are regarded as very effective carbon sinks that can help reduce the rise in CO_2 levels in the atmosphere (Coleman 2018; Bhattacharya 2019). When plantation forestry is conducted using superior silvicultural techniques, its carbon productivity (Mg ha^{-1} yr^{-1}) exceeds that of natural forests (Lal and Singh, 2000; Baishya et al. 2009). Aboveground carbon stocks have been paid attention for years because they are easy to quantify, either through direct ground observations like field allometric equations or derived results from remote sensing like vegetation index maps (Santantonio et al. 1977; Robinson 2007). Climate, location, land use systems, stand age, plantation structure, and silvicultural methods are the primary determinants of carbon stocks in forest biomass pools (Guo and Gifford 2002; Kaul et al. 2010; Kumar et al. 2016), and generally, plant biomass increases gradually with stand age following long normal distribution (Kumar et al. 2021).

Research of above- and belowground carbon dynamics according to stand age during the normal rotation cycle is essential for a better understanding of the processes that reduced the carbon storage in plantations and recommending effective management of carbon storage. Furthermore, a deeper understanding of these plantations

could help with carbon assessments at the regional, national, and global levels due to their importance. Therefore, in this study, we compared total carbon in a *Eucalyptus* plantation at seven stages of development (age 2, 5, 7, 8, 11, 13, and 21 years).

Furthermore, this study would answer the following questions: (i) How do aboveground and belowground biomass and carbon change as a function of stand age (ii) How do above- and belowground biomass and carbon differ depending on their stand structure. Therefore, this study hypothesized that as stand age increased, the biomass and carbon storage of *E. camaldulensis* would show divergent trends and that the contribution of tree biomass to total carbon would rise significantly over time. This study also hypothesized that total carbon has a significant positive relationship with a diameter at 130 cm (DBH), density, basal area, stand height, crown length, crown width, and tree bole height. Inventory data were combined and analyzed to answer the study questions and test the hypotheses. The age-wise contribution to carbon stocks and the relationship between total carbon and stand structure (e.g., mean DBH, density, mean basal area, mean height, mean crown length, mean crown width, and mean bole height). Their variation with age was also evaluated and presented. This study's results might be useful in evaluating potential carbon sequestration in *Eucalyptus* trees and determining appropriate forest management methods to combat climate change.

MATERIALS AND METHODS

Study site

The research was carried out in several sub-districts (Upazilas) under Kurigram District, Bangladesh, which are between 25°.023' and 26°.014' N latitudes and 89°.027 'and 89°.054' E longitudes (Figure 1). The study area includes a humid subtropical climate with a dry winter and a hot summer (Mahmud et al. 2018). The annual temperature ranges from 11.20 to 32.3°C, with an average annual rainfall of 2931 mm (BBS 2013).

Eight plots were established for each age class of 2, 5, 7, and 8; five plots for 11; six for 13 years; and two for 21 years of age, considering the availability of plots in different years. Thus, 45 sample plots (10 m x 10 m) were established, covering a 4,500 m^2 area by a systematic simple random sampling method in *E. camaldulensis* plantation. The trees in the research plots were all given numbers, and the total height (H), diameter at breast height (DBH), crown width (CW), crown length (CL), and bole height (BH) of each tree were measured in March 2021.

Field measurement

Diameter tapes were used to determine the DBH at 1.3 m, and total tree height and bole height were measured with the Haga altimeter. The crown diameter was calculated by taking the arithmetic average of the horizontal crown diameter examined by measuring tape on the north-south and east-west axes. The crown length was calculated by subtracting bole height from the total tree height.

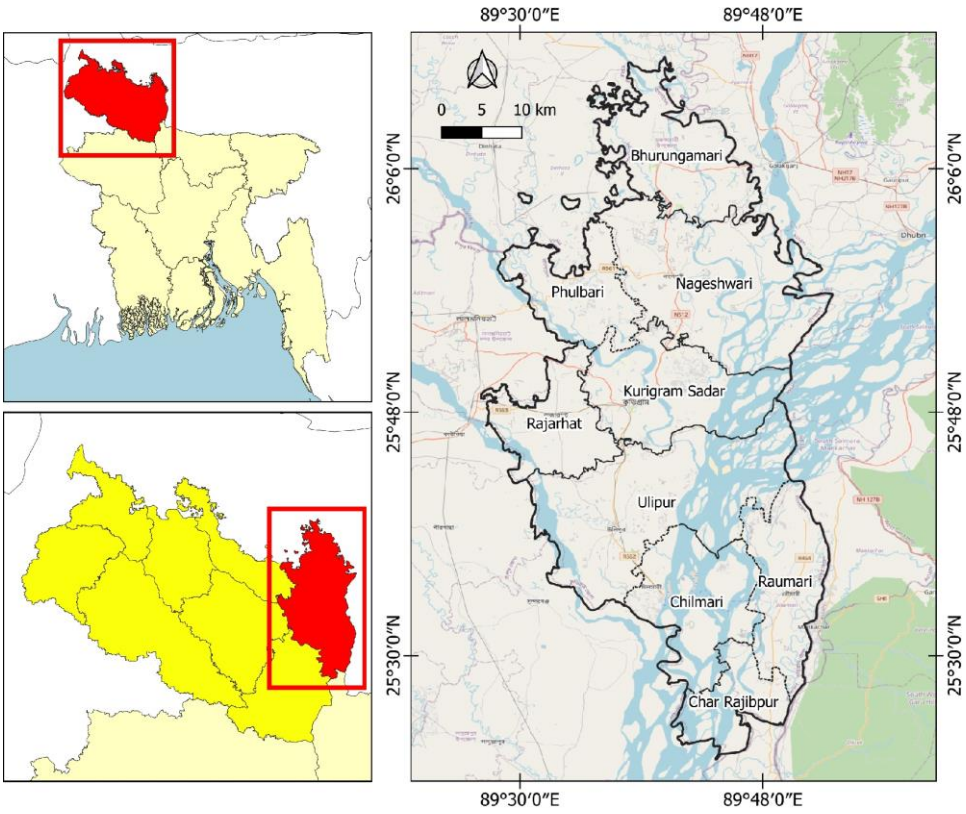

Figure 1. Map of the study area in Kurigram District, Bangladesh

Estimation of biomass and carbon stocks

Each individual's aboveground biomass of *E. camaldulensis* was estimated using allometric relationships between DBH, height, and biomass using a method developed by Hossain et al. (2020).

$$Ln (TAGB) = - 2.663 + 1.915 Ln (D) + 0.832 Ln (H)$$

Where: TAGB = total aboveground biomass (kg), D = DBH, and H = height

The regression model developed by Cairns et al. (1997) was used to estimate belowground biomass, which depends on information on aboveground biomass.

$$BGB = \exp (-1.0587 + 0.8836 \times \ln AGB)$$

Where: AGB denotes aboveground biomass, and BGB denotes belowground biomass

The following formula calculates the Mean Annual Increment (MAI) of biomass:

$$MAI \text{ of biomass} = (\text{Total biomass}) / \text{age (years)}$$

A conversion factor of 0.47 was used to quantify carbon stocks as suggested by the IPCC (2006),

$$Carbon = biomass \times 0.47$$

All the biomass and carbon were expressed as Mg ha^{-1}

Statistical analysis

Before the ANOVA test, the normality and homogeneity of variance assumptions were met. Then, the variations in biomass and carbon stocks, as well as stand age, were studied using a one-way analysis of variance (ANOVA). Additionally, after a significant difference was observed, pairwise comparisons were made using post hoc testing (Tukey's HSD). Finally, the relationship between biomass stocks and stand structural factors was also tested using correlation regression. A significance value of $p < 0.05$ was used for all statistical studies to display the results. The R version 3.1.5 (R Core Team 2017) was used for all statistical analyses and figures.

RESULTS AND DISCUSSION

Data from seven age classes (i.e., 2, 5, 7, 8, 11, 13, and 21 years) of *E. camaldulensis* showed differences in structural variables such as mean density, basal area, height, DBH, bole height, crown length, and crown width. The lowest basal area, height, DBH, bole height, crown length, and crown width are 0.8 ± 0.0 $m^2 ha^{-1}$, 4.7 ± 0.2 m, 2.0 ± 0.1 cm, 3.2 ± 0.2 m, 1.5 ± 0.2 m and 1.8 ± 0.5m, respectively, without mean density 1637± 302 tree ha^{-1} which is the highest in two years of plantation (Table 1). On the other hand, the highest basal area, height, DBH, bole height, crown length, and crown width are 5.8 ± 0.1 $m^2 ha^{-1}$, 30.9 ± 0.9 m, 42.7 ± 0.1 cm, 14.9 ± 0.7 m, 16.1 ± 0.2 m and 7.6 ± 0.4 m respectively, without mean density 400 ± 0 n ha^{-1} which is the lowest in 21 years of plantation (Table 1).

Aboveground and belowground biomass (Mg ha^{-1}) increased significantly with stand age, with the highest and lowest above and belowground biomass found at 21 and 2 years of age, respectively. Similarly, above and belowground carbon (Mg C ha^{-1}) increased with stand age, with the highest and lowest above and belowground carbon found at 21 and 2 years of age, respectively (Figure 2).

The current study observed a strong positive relationship between total carbon (Mg C ha^{-1}) with mean DBH (R^2=0.94, p<2.2e-16) and mean height (R^2=0.90, p<2.2e-16). In the meantime, this study also observed a strong positive relationship of total carbon (Mg C ha^{-1}) with the mean basal area (R^2=0.76, p<8.6e-15), mean crown width (R^2=0.84, p<2.2e-16), mean crown length (R^2=0.8, p<2.2e-16) and mean bole height (R^2=0.79, p<2.2e-16) but a negative relationship with density (R^2=0.75, p<1.3e-14) (Figure 3).

The highest aboveground carbon (302.6 ± 10.9 Mg C ha^{-1}) and belowground carbon (49.4 ± 1.6 Mg C ha^{-1}) were found for 21 year's age *Eucalyptus* plantation (Figure 2, Table 2). On the other hand, the lowest aboveground (0.8 ± 0.2 Mg C ha^{-1}) and belowground carbon (0.3 ± 0.1 Mg C ha^{-1}) were found for two years of age *Eucalyptus* plantation. The mean above and belowground carbon of all age classes is (145.8 ± 8.3 Mg C ha^{-1}) and (25.1 ± 1.3 Mg C ha^{-1}), respectively (Table 2). The mean increment of *E. camaldulensis* increases sharply at a young age (i.e., up to seven years) and decreases (at eight years). Again, the increasing trend observed up to 11 years afterward decreased sharply to 21 years (Figure 4).

Table 1. Stand structure of different age *Eucalyptus* plantation

Age	Density (n ha^{-1})	Basal area ($m^2 ha^{-1}$)	Height (m)	DBH (cm)	Bole height (m)	Crown length (m)	Crown width (m)
2	1637± 302	0.8 ± 0.0	4.7 ± 0.2	2.0 ± 0.1	3.2 ± 0.2	1.5 ± 0.2	1.8 ± 0.5
5	1438± 168	1.7 ± 0.3	10.6 ± 0.4	11.9 ±0.5	7.1 ± 0.6	3.4 ± 0.4	3.6 ± 0.1
7	1412 ± 180	4.5 ± 0.3	11.9 ± 0.9	19.8 ± 0.8	7.5 ± 0.5	4.4 ± 0.4	3.1 ± 0.8
8	1187 ± 64	4.7 ± 0.3	12.8 ± 0.4	22.3 ± 0.7	7.6 ± 0.5	5.2 ± 0.5	3.5 ± 0.9
11	800 ± 70	4.6 ± 0.5	24.8 ± 1.0	26.9 ± 1.1	17.5 ± 0.8	7.3 ± 1.1	5.2 ± 0.6
13	716 ± 75	4.6 ± 0.3	27.6 ± 1.6	28.5 ± 0.8	18.9 ± 1.4	8.7 ± 1.9	4.5 ± 0.4
21	400 ± 0	5.8 ± 0.1	30.9 ± 0.9	42.7 ± 0.1	14.9 ± 0.7	16.1 ± 0.2	7.6 ± 0.4

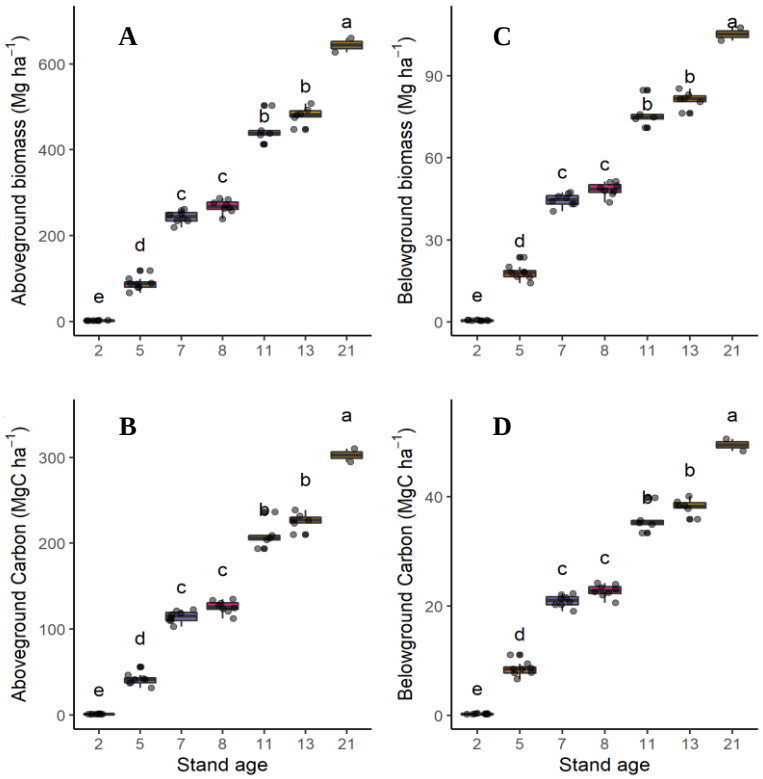

Figure 2. Boxplots showing changes in above and belowground biomass and carbon with stand age in a *Eucalyptus* plantation: A. Aboveground biomass, B. Aboveground carbon, C. Belowground biomass, D. Belowground carbon. The Tukey-HSD post hoc test, which was adjusted from one-way ANOVA, is indicated by different letters on the top of the boxes

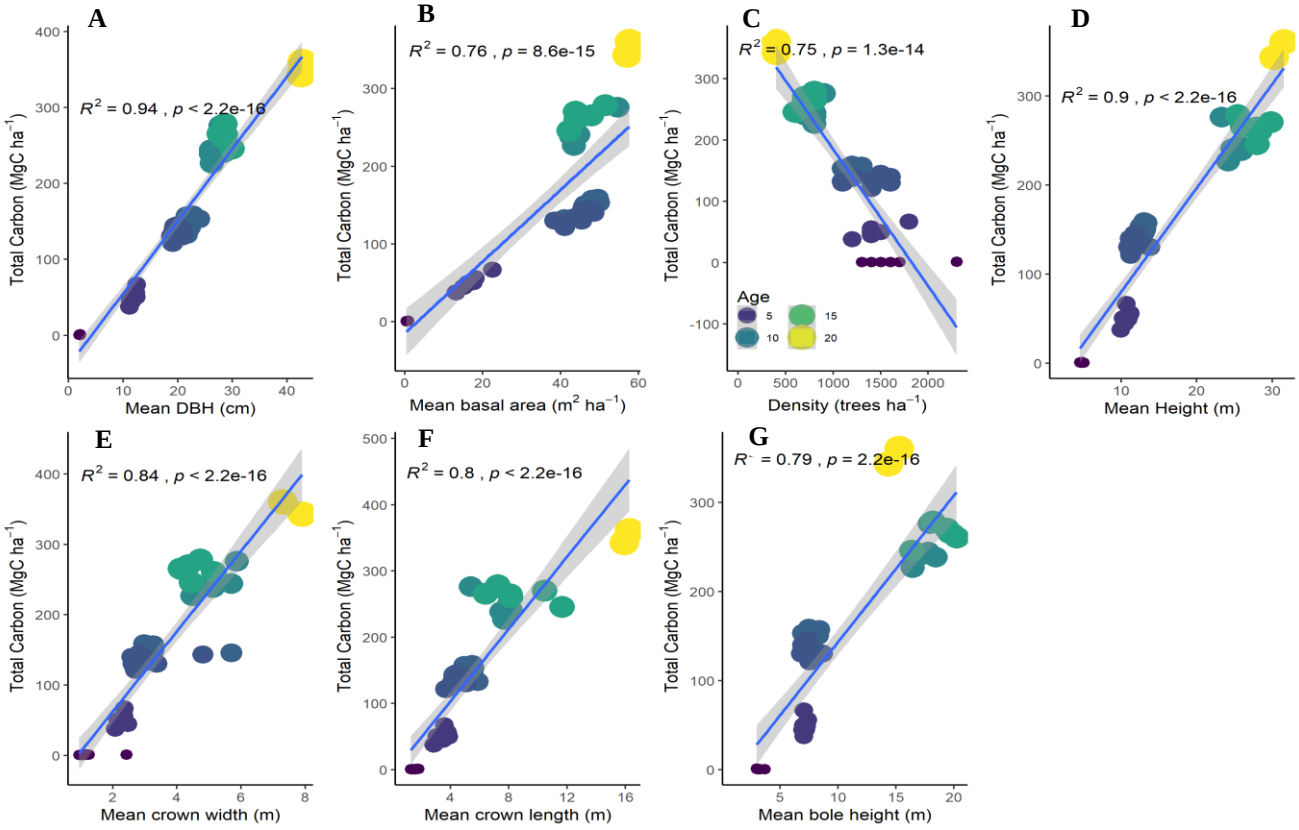

Figure 3. The relationships between estimated total carbon stocks in *Eucalyptus* plantation and stand structural attributes: A. Diameter at breast height (DBH), B. Basal area, C. Stand density, D. Tree height, E. Crown width, F. Crown length, G. Bole height. The larger the points, the older the stands

Table 2. Biomass (Mg ha^{-1}) and carbon stocks (Mg C ha^{-1}) of different age *Eucalyptus* plantation

Age (years)	Aboveground biomass (carbon)	Belowground biomass (carbon)	Total biomass (carbon)
21	643 ± 23.2 (302.6 ± 10.9)	105 ± 3.3 (49.4 ± 1.6)	748 ± 26.5 (352 ± 12.5)
13	481 ± 20.1 (226.1 ± 9.5)	81 ± 3.0 (38.2 ± 1.4)	562 ± 23.1 (264.3 ± 10.9)
11	446 ± 34.1 (209.7 ± 16.5)	76 ± 5.1 (35.7 ± 2.4)	522 ± 39.2 (245.4 ± 18.9)
8	267 ± 15.6 (125.8 ± 7.3)	48 ± 2.5 (22.7 ± 1.2)	315 ± 18.1 (148.5 ± 8.5)
7	243 ± 14.2 (114.3 ± 6.7)	44 ± 2.3 (20.9 ± 1.0)	287 ± 16.5 (135.2 ± 7.7)
5	88 ± 15.4 (41.5 ± 7.3)	18 ± 2.8 (8.5 ± 1.3)	106 ± 18.2 (50 ± 8.6)
2	1.7 ± 0.4 (0.8 ± 0.2)	0.5 ± 0.1 (0.3 ± 0.1)	2.2 ± 0.5 (1.1 ± 0.3)
Mean	309 ± 17.5 (145.8 ± 8.3)	53 ± 2.7 (25.1 ± 1.3)	363 ± 20.3 (170.9 ± 9.6)

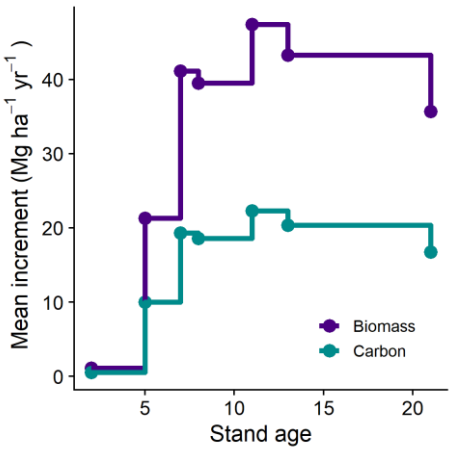

Figure 4. Visualizes the mean biomass and carbon increment in *Eucalyptus* plantations by stand ages

Discussion

This study reveals that above- and belowground biomass and carbon varied with stand age (Table 2), which supports the previous hypothesis. Because *Eucalyptus* is a rapidly growing species, there is a significant difference in above and belowground carbon and biomass with age (Figure 2). Therefore, the total carbon and biomass are greater in the 21-year *Eucalyptus* plantation following 13, 11, 8, 7, 5, and 2 years. Zhang et al. (2012) found a similar result: the total biomass and carbon production of *E. camaldulensis* vary with age. Zhang et al. (2018) found that middle-aged and mature *Eucalyptus* plantations produced considerably more total biomass carbon than younger ones ($P < 0.01$). Du et al. (2015) found the amount of carbon stored in tree biomass increased as the forest became older, from 3.1 Mg ha^{-1} at age 1 to 24.0, 31.6, 42.6, and 70.1 Mg ha^{-1} at ages 2, 3, 4-5, and 6-8 years, respectively. Ulman and Avudainayagam (2014) discovered that total biomass carbon content ranged from 10.25 t ha^{-1} (one-year plantation) to 82.16 t ha^{-1} (four-year plantation) for *Eucalyptus tereticornis* Sm. in the Forest College and Research Institute at Mettupalayam in India. According to Joshi et al. (2013), carbon sequestration by an 8-year *Eucalyptus* hybrid plantation in the Terai region of the central Himalayas was 7.88 t Cha^{-1} per year. Ram et al. (2011) found *E. tereticornis* clones planted in a strip pattern in a water logging site in Haryana stored 15.5 t ha^{-1} of carbon at the 5-year 4 months old plantation. According to Kumar et al. (2021), the total carbon stock (plant + soil) in an 8-year plantation of *E. tereticornis* ranged from 114.1 to 118.8 Mg C ha^{-1} in semi-arid regions of Northwest India.

On the other hand, total carbon has a strong positive relationship by stand structural parameters such as height, DBH, basal area, crown height, crown length, and bole height but a negative relationship with density (Figure 3), which supports the second hypothesis. This positive relationship (without stand density) was because more height, basal area, DBH, crown height, crown length, and bole height indicate greater biomass. Therefore, more biomass indicates more carbon stock. Chave et al. (2005) stated that DBH, height, and canopy spread closely correlate to biomass. Total aboveground biomass is very strongly related ($R^2 = 0.99$) to DBH (Kuyah et al. 2012) and tree volume (Henry et al. 2009). Wider spacing provided enough space and less competition for higher biomass accumulation, which explains the negative relationship between density and total carbon stock (Kumar et al. 2021). However, Jaman et al. (2016) found that the stem density ($R^2 = 0.258$) and DBH ($R^2 = 0.182$) of tree species had no strong relationship with carbon stock at the home garden in the Rangpur District of Bangladesh. Chauhan et al. (2009) found that in an *E. tereticornis* plantation, tree stem C storage (4.20 t ha^{-1}) and total C storage (9.36 t ha^{-1}) in Punjab, India.

Biswas and Hasan (2020) found aboveground biomass and carbon at 116.397 Mgha^{-1} and 58.199 Mgha^{-1} for *E. citriodora* at a roadside agroforestry plantation in Sadar Upazila, Mymensingh district, Bangladesh. They also found a strong relationship between basal area and aboveground carbon stock ($R^2 = 0.874$, p-value<0.05). Also a very strong relationship between stand density ha^{-1} and total aboveground carbon stock ($R^2 = 0.997$, p-value<0.05) for 23 species, including *E. citriodora*. This different result could be due to limited resources like water and nutrients in our study area (Tamang et al. 2021) and monoculture *Eucalyptus* plantation. Stands accumulated biomass quickly as they grew older, well above the rate of accumulation observed in other tropical and subtropical plantation studies (Singh and Toky 1995; Bauhus et al. 2004; Zewdie et al. 2009).

The reason for the variation of total biomass and carbon in *Eucalyptus* species is not only the variation of age but

also due to their rapid growth; the case of *Eucalyptus* trees form a forest with low-biomass density (Zhang et al. 2012). Climate factors, particularly temperature and water availability, impact potential forest biomass output and carbon density on a global and regional scale (Lieth 1975). The rising temperature and decreasing precipitation greatly influence forest vegetation's structure, functions, dynamics, and distribution. These changes would affect the forest vegetation's carbon sequestration potential (CSP) (Hui et al. 2017; Zhou et al. 2022). Site condition and soil characteristics are important at the local level for preserving the quality of the water and sustaining long-term site production, and soil properties are significantly influenced by the age of the plantation (Omoro et al. 2013; Tamang et al. 2021; Schoonover and Crim 2015). Moreover, organic matter quality, which is related to species, and thus forest type, soil type, and texture are important aspects, too (Jobbágy and Jackson 2000). However, to a greater or lesser extent, human activities and management identify the true biomass and carbon density (Brown and Gaston 1995). The mean increment ($Mgha^{-1}yr^{-1}$) of *E. camaldulensis* increases sharply up to seven years, then decreases in years eight and nine, but again increases up to 11 years, then sharply decreases up to 13 years, and gently decreases up to 21 years (Figure 4). According to Kumar et al. (2021), annual growth in tree height, DBH, biomass, and carbon storage of *E. tereticornis* was high for the first six years before slowing down for the next eight years, which is nearly similar to these findings. Furthermore, Ram et al. (2011) and Kumar et al. (2016) observed a striking similarity in the growth and biomass of *E. tereticornis* and *Populus deltoides* in plantation forestry in North-Western India. Shin et al. (2007) found the highest net mean annual increment (MAI) in carbon stock at 9.83 (SE 1.50) t $Cha^{-1}yr^{-1}$ in the *E. camaldulensis* stands, followed by *A. mangium* (7.48 t C $ha^{-1}yr^{-1}$, SE 0.66) and the lowest was in the *Gmelina arborea*, at 0.25 t C $ha^{-1}yr^{-1}$ (SE 0.64) in Bangladesh. Du et al. (2015) found that annual rates of biomass carbon accumulation in trees in the *Eucalyptus* stand were 3.1, 20.9, 7.6, 5.0, and 9.2 Mg ha^{-1} y^{-1} for ages 1, 2, 3, 4-5, and 6-7 years, respectively. Shin et al. (2007) stated that the largest net increment (10 t $ha^{-1}year^{-1}$) was found in 8-year-old *Acacia auriculiformis* A.Cunn. Ex Benth. and 8-year-old *E. camaldulensis*, followed by 18-year-old *E. camaldulensis*, while the lowest was reported in the *G. arborea* plantation among 13 plantation species in the hilly area of Bangladesh. Several variables, including planting material, density, growth circumstances, site attributes, age, structure, and, most crucially, management strategies, influences the total biomass output from a plantation (Goswami et al. 2014). The Mean height, DBH of the lowest age (2 years old) *Eucalyptus* tree is 4.7 ± 0.2 m, 2.0 ± 0.1 cm, and the mean height, DBH of the highest age (21 years old) is 30.9 ± 0.9 m, 42.7 ± 0.1 cm respectively (Table 1). Dogra (2011) found carbon sequestration rates of 236.8 kg per tree at height and a DBH of 24 m and 30 cm, respectively, for *E. tereticornis* in India. *E. camaldulensis* can reach up to 20 m tall and rarely exceeds 40 m; if properly managed, this species will be highly economical (Hassan 1994).

In conclusion, this research reveals that *Eucalyptus* is a fast-growing forest tree with significant potential for biomass and carbon sequestration. This study also found that biomass and carbon of *Eucalyptus* plantations increase with stand age. A positive and strong relationship exists between total carbon and structural attributes such as stand height, DBH, basal area, density, crown width, crown length, and bole height. Low-density stands of *E. camaldulensis* accumulate more biomass and carbon than high-density stands. This study only examines the biomass and carbon productivity changes in *Eucalyptus* plantations as a function of stand structure and stand age. Still, possible responsible factors for this were not observed. Thus, future research could be interesting by covering broad geographical ranges and highlighting the soil variables.

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