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Evaluation of fruit production, carbon sequestration and economic potential of mangoes (*Mangifera indica* L.) in degraded lands of Indian Himalaya

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ABSTRACT: *Experiment was conducted on mango at ICAR-Indian Institute of Soil and Water Conservation, Dehradun during 1995-2020. Mango cultivar 'Mallika' was the most vigorous and attained maximum plant height (6.80 m), canopy volume (220.25 m^3) produced highest fruit yield (90.81 kg $tree^{-1}$), litter production (5.35 tha^{-1}), fine root production (847.21 g m^{-2} yr^{-1}) and conserved 10.90 cm moisture in the soil profile upto 1.20 m depth. Whereas the lowest plant height (4.50 m), canopy volume (147.73 m^3) in Amrapali cultivar, soil moisture conservation and lowest fruit yield (50.31 kg $tree^{-1}$) in Ramkela were recorded in 25 years of orchard life and 20 Year of fruiting life of mango. The maximum fruit qualities like fruit weight (g), pulp content (%), totals soluble solids (^{0}Brix), total sugar (%), reducing sugar (%), non-reducing sugar, β carotene (%) in Mallika cultivar whereas maximum acidity (%) and Vit.-C in Ramkela cultivar of mango were observed during 1995-2020 on degraded lands. The biomass productivity comprising stem, branches and roots was the highest in Mallika (82.37 Mg ha^{-1}), carbon stock (40.02 Mg C ha^{-1}) with carbon sequestration rate (1.60 Mg C $ha^{-1}yr^{-1}$) followed by Bombay green (1.50 Mg C $ha^{-1}yr^{-1}$) and Langra (1.48 Mg C $ha^{-1}yr^{-1}$). Net present value of mango cultivars ranged from 32,068 USD in Mallika to 20,514 USD in Bombay Green cultivars of mango. The benefit cost ratio ranged from 3.26 (Mallika) to 2.0 (Bombay Green), thereby presenting adequate choice to the cultivators / growers to select the appropriate cultivars for specialization. The Mallika cultivar of mango outperformed considering demand of pulp/juice industries and Ramkela cultivar well qualified for pickle industries under degraded lands.*

KEY WORDS: Carbon stock, degraded lands, Fruit yields, Fruit quality parameters, Growth performance, Mango cultivars, Tree biomass,

INTRODUCTION

In India, 120.72 million hectares area (36.7%) is subjected to various forms of land degradation. Out of this, 73.3 (22.3%) million hectares of degraded land is affected by water erosion (Anonymous, 2010). Indian north western Himalayan region (NWHR) is more vulnerable to land degradation due to undulating land, eroded vegetation and unconsolidated soil. These lands are characterized as gravely riverbed lands with shallow soil depth and high gravels content, poor soil organic carbon, etc (Mehta et al, 2018; Rathore, et al. 2013; Saroj, et. al 1994). Moreover, climate change has emerged as a global issue affecting the great Himalayas. This increases the frequency of extreme events, leading resource degradation (Haile et al. 2008; Rathore et al. 2012).

Various fruit species (mango, peach, litchi, citrus, guava, jackfruit, pomegranate, etc) are commercially grown in the region depending on the micro-climatic and edaphic constraints but their productivity is by and large low in comparison to national averages (Rathore et al. 2016). In the present context, horticulture and forestry sector (HFS) have the greatest potential for sequestering carbon in soil and constitute a major carbon sink as biomass (Brown et al. 1992). In India, 79.42 million ha (mha) area (24.16%) is under forest cover, of which, 6.70 mha is under fruit cultivation that produced 98.58 million tones (MT) fruits with productivity (14.82 tha^{-1}) and shares 8.50% to total tree cover (NHB 2019). However, mango (*Mangifera indica* L) has very deep root system and can be a better option for utilization of degraded lands covering 2.30 mha lands. Moreover, mango is the national fruit of India being cultivated throughout the country because of its wide adaptability to various soil and climates of India, besides its rich biodiversity, high nutritive value, economic viability, etc (Rathore et al. 2013). Mango shares 34% (2.30 m ha) area and 21.0% (20.80 m.t.) production of total area and production of fruits in India with 9.0 tha^{-1} productivity (NHB, 2019).

Fruit trees are important component of agroforestry systems (AFSs), where fruit trees are grown with or without crops, which provides the stable output to the farmers in the region. The existence of fruit based systems (FBSs) have many advantages in reducing landslides, soil erosion, conserving moisture and carbon sequestration in addition to livelihood, nutritional and restoration of degraded lands (Yadav and Bisht 2014). Besides, FBS play an important role in carbon cycles in reducing carbon dioxide (CO_2) emissions and enhancing carbon sinks to meet the twin objectives of climate change adaptation and mitigation. (Murthy et al. 2013). Carbon sequestration is a mechanism for removal of CO_2 from the atmosphere and storing in different components of tree biomass and soils (Chavan and Rasal 2012). The estimates of sequestration potential in AFSs are highly variable ranging from 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$ (Nair et al., 2009). Enhancing sequestration is one of the major strategies of reducing atmospheric CO_2 (Dash 2010). Terrestrial vegetation including horticulture stores 350 pg carbon (Dixon et al. 1994) contributed annual CO_2 emission to the atmosphere due to continuous deforestation (IPCC 2000). The transition of land use systems from lesser (agriculture) to higher biomass (FBSs) will help in reducing CO_2 through sequestration process (Kimaro et al. 2011).

Globally, soils are estimated to contain approximately 1,500 GT of carbon (Batjes 1996). The exchange of greenhouse gases between terrestrial ecosystems and the atmosphere takes place due to land use and land use changes (Lal 2002; Upadhyay et al. 2005). This has led to an

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increased interest in reducing CO_2 through carbon sequestration by FBSs (Pandya et al. 2013). In India, where a majority of the population is dependent on agriculture and horticulture, which provide a long-term strategy to increase the amount of carbon while still allowing food crop cultivation. ICRAF projected that the carbon market may exceed US$1 trillion by 2025 suggest that significant funds could potentially be available for sustainable development (Anonymous 2009). Estimates of carbon stocks and stock changes in tree biomass are necessary for reporting to the UNFCCC and Kyoto Protocol (Chavan and Rasal 2012).

This paper deals with assessing the fruit production, fruit qualities, tree biomass, carbon sequestration and economic analysis of mango cultivars established under degraded lands in subtropical climate. Besides, it is intended to highlight the ecosystem services and environmental benefits of mango plantations in addition to livelihood, nutrition security and socio-economic benefits.

MATERIALS AND METHOD

Site characteristics and experimental details

Experiment was conducted in mango cultivars during 1995 to 2020 at ICAR-Indian Institute of Soil and Water Conservation, Dehradun on degraded land. Site received 1600 mm yr^{-1} rainfall in subtropical climate at 516.5 m altitude with gravelly soil (<1.0 fit), sandy-loam texture, slightly acidic and poor fertility status. Proportion of gravels increased with increasing soil depth. Mechanical analysis of soil particle (< 2.0 mm) indicated that sand (74.86%), silt (20.74%), clay (4.40%) and bulk density (1.10-1.40 Mg m^{-3}) were observed. One year mango grafts were planted in $1m^3$ pits filled with 50 kg FYM with recommended NPK at spacing of 8x8 m in July, 1995. Drip system was installed for irrigation of mango plants initially (5 years) and channel irrigation was applied during moisture stress period (April to June) considering gravelly soil. Natural resource management (NRM) technologies like mulching, canopy management, soil working techniques (70 gravels and 30% soil volume basis) were uniformly applied in all treatments. The experiment was laid-out in RBD with three replications. Six mango cultivars (C_1=Amrapali, C_2=Mallika, C_3 = Dashehari, C_4 = Langra, C_5 = Bombay green and C_6 = Ramkela) were evaluated for 25 years. Four plants were kept as an experimental unit for recording of data.

Data collection

Observations on plant growth characters (plant height, canopy volume, fruit yield, fruit drop, fruit retention, fruit weight, pulp, stone, peel, crude fibre, acidity, TSS, total sugar, reducing sugar, non-reducing sugar, vitamin C and β carotene) were recorded in the experiments. Plant height was measured with the help pole marked with scale and canopy volume was calculated by using formula (πr^2h). Fruit quality parameters were determined following standard procedure (Rangana 1986). The uniform training, cultural and plant protection practices were followed. Litter production (LP) of mango was collected monthly and summed

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up annually with the help of litter traps of 1x1m size during (January–December) for entire period and weighed by electronic balance after drying in oven and expressed in tha^{-1}.

Sampling of fine roots and estimation of turnover rates:
Sampling was done by sequential coring in mango cultivars during January to December, 2020 at 0-30 cm depth within 1.0 m radius for fine root production. It may lead underestimation of fine root production (Makkonen and Helmisaari 1999) but a widely used method since it directly estimates fine root biomass (Hertel and Leuschner 2002). Soil cores were obtained by driving an edged steel auger and individual cores were placed in polythene bags for washing. Roots (< 1.0 mm diameter) were considered as fine roots (Raizada et al. 2013). Fine roots collected from 0-30 cm depth were dried at 70^0C for 48 hours, weighted, summed up and expressed in g m^{-2}. Root production was determined as total amount of root mass for soil (0-30 cm) and calculated by minimum-maximum method (McClaugherty et al. 1982), which calculates the difference between minimum and maximum of fine root biomass and equates it with production. The rate of fine root production was expressed as $gm^{-2}yr^{-1}$. Turnover rate of fine roots was calculated by dividing annual fine root production with the mean of fine root mass and expressed as yr^{-1}.

Tree biomass
Biomass was estimated by non-destructive method for stem, branch, leave and root parts in 25 year old mango trees. The stem volume of mango was measured including bark and transformed into dry matter by multiplying it with specific gravity (0.52 g cm^{-3}), which was measured by water displacement method in mango cultivars. Likewise, branches of sampled mango were counted and classified into three groups based on their basal diameter, *viz*. < 2, 2–6 and >6 cm. From each of sampled mango trees, two branches /branch group were randomly selected and weighed fresh. Sub-samples of each component were oven dried to constant weight at 65 °C. Using the fresh/dry weight ratio and the number of branches, dry weight was determined. Similarly, Root biomass was estimated considering coarse as well as fine root production.

Carbon estimation in tree and soil
Carbon stock in the different mango cultivars was obtained by multiplying the dry weight of the different tree components by their average carbon concentration. Carbon was assumed to constitute 50% of the ash-free dry mass. Ash content was determined by igniting 1.0 g of powdered sample at 550°C for 6 h in muffle furnace. The carbon stock obtained in the different tree components was summed up to obtain total carbon stock (TCS) in each mango cultivars. The estimated TCSs were converted into CO_2 equivalents using (C × 44/12). Soil organic carbon (SOC) was determined according to Walkley and Black (1934) in all plots at 30 cm soil depth. SOC was computed by multiplying the organic carbon (g kg^{-1}) by bulk density (g cm^{-3}) and depth (cm) and is expressed in Mg ha^{-1}.

Economic evaluation and Statistical analysis
Primary data on inputs (grafts, fertilizers, FYM, irrigation, labour, etc) utilized and outputs (fruit yields) were recorded annually through systematic monitoring. All inputs and outputs

were converted into monetary values to express in a common unit. For this, average prices of each input/output during 1995-2020 were worked out to account for yearly price fluctuations. Year wise total costs and total returns hectare^{-1} were estimated for each cultivar to calculate benefit: cost ratio (BCR). Considering 25 years of experimentation period of mango tree, a discounted rate of eight per cent was utilized for estimating BCR, net present value (NPV) and payback period (PBP) for each mango cultivar evaluated, since returns from investment in a long term bank deposit and was considered an opportunity cost of investment. PBP is the certain number of years after which an investment becomes profitable by cumulative benefits (cash inflows) from the investment becoming higher than the cumulative costs incurred (cash outflows) over the same number of years. BCR analysis was done for each cultivar. The data were subjected to standard analysis of variance technique and statistical analysis for the individual year as well as pooled over the years for different parameters. The mean effect of treatments were compared at $P< 0.05$ level of significance (Gomez and Gomez 1984).

RESULTS

Fruit yield and growth attributes

Results showed that mean plant height, canopy volume, fruit yield, soil moisture, fruit drop and fruit retention were varying significantly among mango cultivars during 1995-2020 (Table 1). The maximum plant height (6.80 m), canopy volume (220.25 m^3), fruit yield (90.80 kg tree^{-1}), soil moisture (10.90 cm), fruit retention (14.20%) and minimum fruit drop (82.80%) were observed in Mallika cultivar of mango whereas minimum plant height (4.50 m) and canopy volume (147.73 m^3) in Amrapali, fruit yield (50.30 kg tree^{-1}) and soil moisture (8.72 cm) in Ramkela, fruit retention (8.02%) in Langra were recorded during 25 years of mango plantations.

Fruit quality parameters

Statistical analysis of data revealed that physical fruit quality parameters (fruit weight, pulp %, peel %, stone %, specific gravity, crude fibre %) and chemical fruit quality parameters (TSS, total sugar, reducing, non-reducing sugar, acidity, β carotene and vitamin C) were varied significantly among mango cultivars during 1995-2020 (Table 2, 3). The maximum fruit weight (382 g fruit^{-1}), pulp (73.73%) minimum peel (13.26%) and stone (13.0%) in Mallika whereas maximum crude fibre (0.89%) in Ramkela were observed among mango cultivars. The lowest fruit weight in Amrapali, minimum pulp, maximum peel & stone in Ramkela and crude fibre in Dashehari were recorded among mango cultivars.

Similarly, among chemical fruit qualities of mango cultivars, the maximum TSS (22.01 ^{0}Brix), total sugar (16.97%), reducing sugar (4.92%), non-reducing sugar (12.05%), β carotene (17,500 µg. 100g^{-1}) in Mallika, whereas maximum acidity (3.54%), vitamin C (92.37 mg/100g) in Ramkela cultivar of mango were registered during entire growing period of mango plantation. The lowest chemical fruit qualities TSS (10.02 ^{0}Brix), sugar (7.51%), reducing sugar (2.92%), non-reducing sugar (4.59%), β carotene (7,256 µg. 100g^{-1}) in Ramkela, minimum acidity (0.23%) in Dashehari and minimum vitamin C (32.98 mg.100g^{-1}) were observed in mango cultivars.

Fine root production

Fine root biomass (FRB), Fine root production (FRP) and fine root production turnover rates (FRTR) were differed significantly in mango cultivars (Table 4). Among mango cultivars, Mallika produced FRB (1049.30 g m^{-2}) and was 22.6 to 39.10% higher over other mango cultivars. Similarly among the seasons, autumn season produced 44.71-84.96 and 79.09-116.81% higher FRB than spring and summer seasons, respectively. Likewise, maximum FRP was also recorded in Mallika (847.21 gm^{-2} yr^{-1}) and was 64.5 to 89.9% higher than other cultivars. Similarly, Mallika was also recorded 26.3 to 40.20% more FRTR over other mango cultivars at 30 cm soil depth.

Litter production

The litter fall was also statistically varied among the mango cultivars (Fig. 1). The maximum litter yield (5.35 tha^{-1}) was rerecorded in Mallika followed by Bombay Green (4.55), Langra (4.34), Dashehari (4.08), Ramkela (3.46) and Amrapali (3.05 tha^{-1}) among mango cultivars in 25 years old plantations on degraded lands. The canopy volume of mango was positively correlated with litter production (r=0.91) of mango cultivars.

Soil fertility

Similarly, soil fertility among mango cultivars also differ significantly (Table 5). Similarly, maximum soil organic carbon (0.74%), nitrogen (0.073%), phosphorus (10.83 ppm) and potash (79.18 ppm) in Mallika cultivar whereas minimum soil organic carbon (0.54%), nitrogen (0.050%), phosphorus (8.02 ppm) and potash (56.49 ppm) in Ramkela were observed among mango cultivars. The initial soil fertility values of soil organic carbon (0.48%), nitrogen (0.043%), phosphorus (7.25 ppm) and potash (49.90 ppm) were recorded before establishment of mango cultivars plantation in 1995.

Biomass and carbon sequestration

Total dry above- and below-ground biomasses were varied significantly among mango cultivars (Table 6). The stem and branch components were accounted for calculation of above ground biomass whereas root biomass was accounted for below ground biomass in mango cultivars. Maximum dry biomass was harvested in Mallika (82.37 $Mgha^{-1}$) and minimum (70.52 $Mgha^{-1}$) with Amrapali cultivar among mango cultivars. Similarly, mean annual increment (MAI) was ranged from 3.29 to 2.82 Mg ha^{-1} $year^{-1}$ in 25 years old among mango cultivars.

Carbon % in different biomass components was observed 48.5, 48.0 and 47.0% in stem, roots and branches, respectively in mango cultivars (Fig. 2). The biomass carbon stocks were also differed significantly among mango cultivars (Table 7). The maximum carbon stock was stored in Mallika (40.02 Mg ha^{-1}) and minimum with Amrapali (34.27 $Mgha^{-1}$) among mango cultivars. Similarly, Carbon sequestration rate was recorded same as of MAI and ranged from 1.60 (Mallika) to 1.37 (Amrapali) Mg C ha^{-1} yr^{-1} among mango cultivars.

Soil organic carbon (SOC) was measured at (30 cm) in 25 years old mango plantations (Table 8). Maximum SOC was recorded (35.97) with Mallika and minimum in Ramkela green (29.33 Mg ha^{-1}) over initial SOC recorded in 1995 (20.70 to 21.56 Mg ha^{-1}) at 30 cm soil depth. Maximum total carbon stock (76.00 Mg ha^{-1}) contributed by soil (35.97 Mg ha^{-1}) and trees (40.03 Mg C ha^{-1}) was also recorded in Mallika with equivalent CO_2 (278.63 Mg ha^{-1}) and minimum TCS (64.46 Mg C ha^{-1}) with equivalent CO_2 (236.35 Mg ha^{-1}) in Amrapali at 30 cm soil depth, respectively.

Economic viability

Economic analysis of mango cultivars on degraded land during 1995-2020 indicated that maximum net present value (NPV) realized with Mallika (USD 32,068 ha^{-1}) which was 19.68 to 56.32.0% higher as compared to other mango cultivars. The NPV values of all the cultivars were higher than the NPV (USD 20,514) of Bombay Green (Table 9). Likewise, highest benefit-cost ratio (3.26) obtained from Mallika and was 14.39, 33.06, 40.52, 52.34 and 63.0% more than Amrapali, Ramkela, Langra, Dashehari and Bombay Green, respectively during 1995 to 2020. The benefit-cost ratio (BCR) among different cultivars was higher than the Bombay Green (2.00). Similarly, the payback period (PBP) of Mallika cultivar was recorded 9.09 to 28.57% lesser than other mango cultivars.

DISCUSSION

Fruit yield attributes

Data revealed that growth parameters (plant height, canopy volume), fruit yield and soil moisture, fruit drop and fruit retention of mango cultivars differed significantly on degraded lands (Table 1) on degraded lands under sub-tropical climate. Mallika cultivar of mango tree attained 32.30 to 51.10%, 16.20 to 28.80%, 18.00 to 80.50%, 21.30 to 80.50, 9.00 to 36.30% higher plant height, canopy volume, fruit yield, fruit retention and moisture conservation, respectively and -3.60 to -10.20% lower fruit drop over other mango cultivars during 1995-2020. The fruit yield was positively correlated with plant height (r=0.72), canopy volume (r=0.71), soil moisture (r=0.80), fruit retention (r= 0.76) whereas fruit drop (r = - 0.84) was negatively correlated with fruit yield of mango among all cultivars. Similarly, soil moisture conservation was also positively correlated with plant height (r = 0.76), canopy volume (r= 0.76), fruit retention (r = 0.93), fruit yield (r = 0.80), and negatively correlated with fruit drop (r= -0.90). Positive correlation indicated that both parameters increase or decrease simultaneously whereas negative correlation reflected inverse relationship. Among six mango cultivars, only two mango cultivars (Mallika and Amrapali) were hybrid which bear fruits every year (regular fruit bearer), one mango cultivar (Dashehari) was partial fruit bearing chance seedling, whereas three mango cultivars (Langra, Bombay green, Ramkela) were alternate fruit bearing chance seedlings (irregular fruit bearers) established on degraded land under subtropical climate (Rathore et al 2010, Ram 1993; Singh 1978). Mallika attained maximum plant height, canopy volume, conserved soil moisture, fruit retention, produced highest fruit yield with minimum fruit drop due to varietal characters like regular bearing habit, biggest fruit size, addition of organic carbon through litter fall, root turnover, mining essential nutrients from deeper layer of soil, better acclimatization (Saroj et al. 1994; Rathore et al. 2011). Canopy spread conserved more moisture in the soil by reducing evaporation losses in *Aonla* (Rao et al. 2011; Rathore et al. 2011, 2013) and fruit yields governed by edaphic, climatic, inherent genetic variations and gene pools of cultivars (Verma et al 2010, Singh and Chaddha, 1981; Negi 2000; Singh 1978).

Table 1 Average morphological characters and fruit yield of mango cultivars grown on degraded lands

Cultivars	Plant height (m)	Canopy volume (m^3)	Fruit yield (kg $tree^{-1}$)	Soil moisture (cm)	Fruit retention (%)	Fruit drop (%)
Mallika	6.80	220.25	90.81	10.90	14.2	82.8
Dashehari	5.00	163.74	60.85	9.56	11.8	87.2
Langra	4.65	161.30	62.76	9.12	8.02	91.1
Bombay green	5.14	158.93	58.90	8.86	10.2	92.2
Ramkela	4.56	156.60	50.30	8.72	9.52	89.7
Amrapali	4.50	147.73	76.95	9.20	12.1	85.9
CD (P=0.05)	0.19	2.32	4.52	0.56	0.55	1.01

Fruit quality parameters

The data reported that physical and chemical fruit quality attributes differed significantly among mango cultivars (Table 2, 3). Among mango cultivars, mallika produced maximum fruit weight (382 g $fruit^{-1}$) which was 119.50 to 218.30% higher than all mango cultivars. Similarly, the fruits of mallika contained 4.20 to 18.70% more pulp, 11.0 to 32.5% thinner peel, 9.40 to 28.60% smaller mango stones whereas Ramkela fruit contained 0.89% higher crude fibre over other mango cultivars. The specific gravity of all mango cultivars was non-significant. Fruit weight was also positively correlated with pulp content (r=0.82). Similarly, among chemical fruit qualities, Mallika fruits recorded 4.5 to 120%, 6.8 to 126% and 13.30 to 141.20% higher Total soluble solid (TSS), total sugar (TS) and β carotene, respectively whereas 831.58 to 1439.13% and 63.89 to 180.08% more acidity and vitamin C content were observed in Ramkela cultivar among mango cultivars.

The Mallika cultivar produced biggest fruit size, pulp content, total soluble solid, total sugar, reducing sugar, non-reducing sugar and β carotene which are important parameters for pulp industries. Whereas more acidity, crude fibre and vitamin C are important qualities of mango for pickle industry recorded in Ramkela cultivar among mango cultivars. The fruit qualities are varietal characters and least influenced by climate of any site (Rathore et al. 2011). The best physical and chemical fruit qualities were observed with Mallika and Ramkela cultivars of mango for pulp/juice industry and pickle industry, respectively because varietal characters like regular bearing habit, biggest fruit size, addition of organic carbon through root turnover, mining essential nutrients from deeper layer of soil, better acclimatization (Saroj et al. 1994;). Canopy spread conserved more moisture in the soil by reducing evaporation losses in *Aonla*

(Rao et al. 2011; Rathore et al. 2011, 2013). Fruit qualities governed by edaphic, climatic, inherent genetic variations and gene pools of cultivars (Verma et al 2010, Singh and Chaddha, 1981; Negi 2000; Singh 1978).

Table 2 Physical qualities of various cultivars in mango grown on non-arable land

Cultivars	Fruit weight (g)	Pulp (%)	Peel (%)	Stone (%)	Specific gravity	Crude fibre (%)
Mallika	382	73.73	13.26	13.01	1.02	0.69
Dashehari	171	67.61	16.67	15.72	1.02	0.56
Langra	174	70.75	14.89	14.36	1.03	0.70
Bombay green	164	67.26	17.43	15.30	1.01	0.61
Ramkela	143	62.14	19.64	18.21	1.02	0.89
Amrapali	120	66.72	17.60	15.68	1.01	0.62
CD (P=0.05)	80	5.89	2.01	2.09	NS	0.12

Table 3 Chemical compositions of various mango cultivars grown on non-arable land

Cultivars	TSS (^{0}Brix)	Total sugar (%)	Reducing Sugar (%)	Non-reducing Sugar (%)	Acidity (%)	β carotene (μg100g^{-1})	Vit. C (mg100g^{-1})
Mallika	22.01	16.97	4.92	12.05	0.38	17500	47.90
Dashehari	20.30	15.42	4.11	11.31	0.23	12565	36.58
Langra	18.51	15.61	4.81	10.8	0.37	12369	56.36
Bombay green	18.10	14.02	4.12	9.9	0.32	10520	35.55
Ramkela	10.02	7.51	2.92	4.59	3.54	7256	92.37
Amrapali	21.07	15.89	4.01	11.88	0.34	15450	32.98
CD (P=0.05)	1.01	0.09	0.04	0.92	0.11	1525	15.86

Fine root production

Fine root biomass (FRB) mostly confined up to 30 cm soil depth in perennial fruit trees because nutrients, irrigation, etc applied to this zone. Fine root biomass (FRB), fine root production (FRP) and fine root turnover rate (FRTR) differed significantly among cultivars (Table 4). The Maximum FRB (1049.30 g m^{-2}), FRP (847.21 g m^{-2} yr^{-1}) and FRTR (0.81 yr^{-1}) was registered in Mallika and minimum with Ramkela cultivar of mango. Canopy volume was positively correlated with FRB (r=0.83), FRP (r= 0.77) and FRTR (r=0.67) which indicated that more canopy volume produced more FRB, FRP and FRTR in the soil which added organic carbon in the soil. Mallika cultivar produced FRB (26.5 to 39.10%), FRP (64.5 to 89.9%) and FRTR (26.30-40.20%) higher as compared to other cultivars. Fine roots were consistent with the availability of moisture and nutrients in cultivars which were raised in artificially created rhizosphere to ensure better plant establishment in the harsh soil conditions. The distribution of fine roots reflects the distribution of available nutrients within an ecosystem. Fine roots are more efficient in absorbing moisture and nutrients (Eissenstat and Yani 2000 and Raizada et al. 2014). An increase in FRB in the warm and humid months

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(July-Sept.) was evident in the post-monsoon season sampling. This increase coincides with the period of active vegetative growth immediately after a hot and dry summer (March-June) induced dormancy. In subtropical and tropical India, maximum FRB has been reported in the wet season (Khiewtam and Ramakrishna 1993; Upadhaya et al. 2005) which corresponds to periods of nutrients release. FRTR in Mallika was higher than other cultivars where FRTRs observed (0.58 to 0.81) in 30 cm soil depth are within range of findings (0.3 to 2.5) as reported by (Raizada et al. 2013). More nutrient availability reduces average root life span and increases turnover because construction cost of roots are low relative to maintenance costs and uptake rates of young roots are high (King et al. 2002).

Table 4 Fine root biomass (0-30 cm soil depth) in mango cultivars on non-arable lands

Species	Fine root biomass (gm^{-2})			Fine root biomass ($g\ m^{-2}$)	Fine root production ($g\ m^{-2}yr^{-1}$)	Fine root turnover rate (yr^{-1})
	Autumn (Max.)	Summer (Min.)	Spring (Med.)			
Mallika	1572.45	725.24	850.15	1049.3	847.21	0.81
Dashehari	1125.84	612.54	750.24	829.5	513.3	0.62
Langra	1160.26	667.35	740.35	856.0	492.91	0.58
B. Green	1092.86	610.24	720.46	807.9	482.62	0.60
Ramkela	1006.54	560.38	695.52	754.1	446.16	0.59
Amrapali	1100.38	585.45	730.76	805.5	514.93	0.64
CD (P=0.05)	45.89	21.67	25.34	10.12	13.27	0.02

Litter production

The litter yield and soil fertility parameters (soil organic carbon, nitrogen, phosphorus, potash) differed significantly among mango cultivars (Fig.1). Litter production (LP) include leaf fall, flower drops, fruit drops, twigs, etc is important carbon inputs to the soil (Fig. 1). Canopy volume (CV) was positively correlated with LP (r=0.91) which also indicated that more CV added more litter to the soil. In this case, Mallika produced maximum litter (5.35 tha^{-1}) and was 17.6 to 75.4% higher than other mango cultivars. Litter depends on canopy size, leaf density and soil moisture of tree (Rathore et al. 2011). Mango is an evergreen tree so litter fall takes place throughout the year (Rathore et al. 2012, 2020, 2021). Mango added bio-litter (6.3 tha^{-1}) and improved not only soil health but also soil moisture retention capacity (Murovhi et al. 2012). The litter yield of aonla (6.6 tha^{-1}) was recorded which improved soil properties and moisture conservation (Dubey et al. 2015). Organic carbon was positively correlated with LP because all these attributes added humus in soils. The increase in available nutrients was ascribed to nutrient mineralization from litter, fine roots and release of nutrients from residual soil reserves (Laik and Dash 2009).

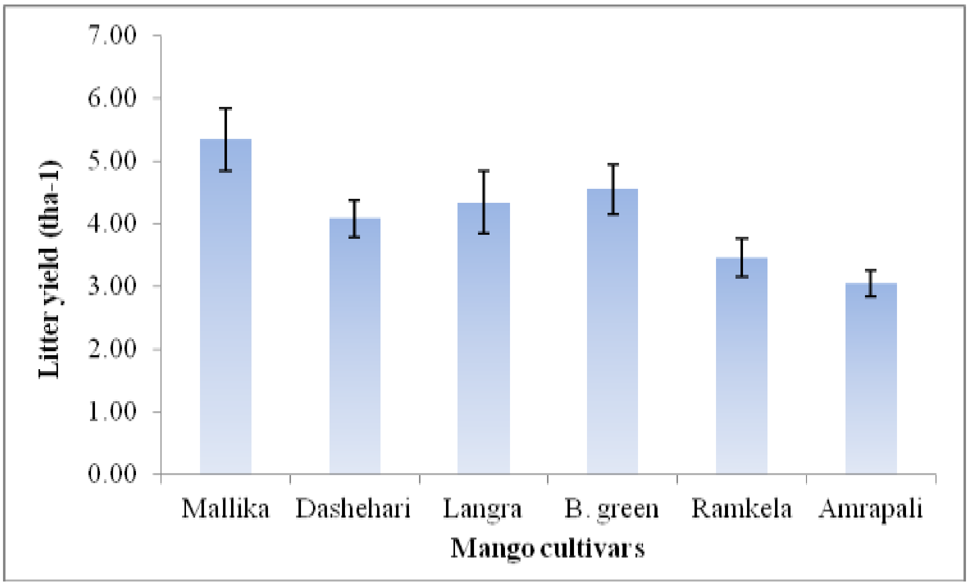

Fig. 1 Litter fall in mango cultivars grown on degraded land

Soil fertility

The soil fertility parameters statistically varied among mango cultivars (table 5). The maximum soil organic carbon (0.74%), nitrogen (0.073%), phosphorus (10.83 ppm) and potash (79.18 ppm) in Mallika cultivar of mango with minimum soil fertility values in Ramkela in 2020 among mango cultivars. The initial soil fertility values of soil organic carbon (0.48%), nitrogen (0.043%), phosphorus (7.25 ppm) and potash (49.90 ppm) were recorded before establishment of mango cultivars plantation in 1995. The improvement in soil organic carbon (12.50-54.17%), nitrogen (11.63-69.77%), phosphorus (11.72-49.38%) and potash (13.21-58.68%) was observed among mango cultivars after 25 years of plantation is due to fine root production (406.54-564.38 g m^{-2} yr^{-1}), litter fall addition in the soil (1.05-1.53 tha^{-1}), recycling of weed biomass in the soil, application of farm yard manures (10.0 tha^{-1}). About 7.2-37.0%, 9.0-52.10%, 8.8-35.0 and 6.9-40.20% higher soil organic carbon, nitrogen, phosphorus and potash were noticed under Mallika plantation among the mango cultivars is due to vigorous tree growth of Mallika produced highest tree biomass attained more canopy volume added maximum litter in the soil and fine root production which conserved more soil moisture which helped in attaining vigorous growth under proper nutrient management. (Rathore et al 2013).

Table 5 Fertility status of the soil under mango cultivars on non-arable lands

Cultivars	Organic carbon (%)	Nitrogen (%)	Phosphorus (ppm)	Potash (ppm)
Mallika	0.74	0.073	10.83	79.18
Dashehari	0.69	0.067	9.95	74.07
Langra	0.68	0.064	9.20	73.40
B. green	0.58	0.054	8.61	65.29
Ramkela	0.54	0.048	8.10	56.49
Amrapali	0.56	0.050	8.02	60.30
Initial value	0.48	0.043	7.25	49.90
CD (5%)	0.08	0.011	2.11	8.20

Biomass and carbon sequestration

Total dry above-ground biomass (stem and branch) and below-ground biomass (roots) varied significantly in 25 years mango (Table 6). The maximum dry biomass (82.37 Mg ha^{-1}) was recorded in Mallika cultivar of mango followed by Bombay green, Langra, DAshehari, Ramkela and Amrapali which was 6.89 to 16.80% higher biomass among cultivars. Similarly, mean annual increment (MAI) was also observed with Mallika (3.29 Mg ha^{-1} $year^{-1}$) and minimum in Amrapali in 25 years. The dry Biomass depends upon a number of factors, *viz.*, growth habit of the species, soil type, clay content, soil composition, rhizospheric soil, tree stands, age, tree ideotype, climatic suitability, training, pruning, heading back, tree management practices and their interactions with below-ground components (Selvaraj et al. 2016; Rathore et al. 2016, 2020, 2021; Niu and Duiker 2006; Jana et al. 2009). Distribution of root systems in space and time is usually influenced by environment, genetic and edaphic factors (Huck, 1983). Further, variation in biomass in the present study is also attributed to sampling difficulties in estimating root biomass. The contribution of above- and below-ground biomass among cultivars ranged 71-74% and 26-29%, respectively, the total biomass of Mallika cultivar mango was slightly higher biomass (82.37 Mg ha^{-1}) observed in 25 years mango plantation under subtropical climate on degraded than mango biomass (80.74 Mg ha^{-1}) at density of 220 trees ha^{-1} after 20 years under topical climate (Selvaraj et al. (2016) is due to age difference and climatic suitability.

Table 6 Biomass of different tree components of mango cultivars (Mg ha^{-1}) grown on non-arable lands

Cultivars	Stem	Branch	Above ground	Below ground	Total biomass	MAI ($Mgha^{-1}year^{-1}$)
Mallika	45.97	13.90	59.87	22.50	82.37	3.29
Dashehari	41.14	11.98	53.12	21.76	74.88	3.00
Langra	43.30	12.47	55.77	20.46	76.23	3.05
B. green	42.64	12.58	55.22	21.84	77.06	3.08
Ramkela	41.46	11.35	52.81	19.73	72.54	2.90
Amrapali	40.89	11.05	51.94	18.58	70.52	2.82
CD (5%)	0.58	0.01	-	0.36	-	-

*MAI= mean annual increase in mango tree biomass

Carbon % in different biomass components were ranged between 49.2 (stem) to 47.9% (branch) among cultivars (Fig. 2). A similar trend of carbon concentration was also observed by (Selvaraj et al. 2016; Negi et al. 2003) in fruit trees in India. Carbon stocks (CS) and carbon sequestration rate (CSR) increase among mango trees is similar to the mango tree biomass in 25 years. CS was cumulative and positively correlated with years (r=0.97). CS ranged from 40.03 (Mallika) to 34.27 Mg ha^{-1} (Amrapali) among cultivars in 25 years old trees (Table 7). Similarly, carbon sequestration rate was also recorded highest with Mallika (1.60 Mg ha^{-1} $year^{-1}$) followed by Bombay Green (1.50), Langra (1.48), Dashehari (1.46), Ramkela (1.41) and minimum CSR with Amrapali (1.37 Mg ha^{-1} $year^{-1}$) during 25 years of mango cultivars under degraded lands. CS refers to the absolute carbon amount held at the time of inventory, whereas, CSR refers to removal of carbon from the atmosphere and depositing in a reservoir (Takimoto et al. 2008). Large C stock does not necessarily mean a large C sequestration potential. Therefore, total carbon sequestration and carbon sequestration rates were estimated in the mango cultivars. CSR ranged from 1.60 (Mallika) to 1.37 Mg C ha^{-1} yr^{-1} among mango cultivars in 25 years (Table 7). CS in mango trees depends on biomass of trees which was influenced by many factors like soil, tree ideotype, soil fertility status, moisture, climatic factors, etc (Selvaraj et al. 2016; Rathore, et al. 2016, 2020, 2021). The similar tree carbon stocks (40.37 Mg C ha^{-1}) was reported in 20 years mango plantation in tropical climate of India (Selvaraj, et al. 2016) because author considered 50% carbon in mango biomass, tree density (220 ha^{-1}), growing period (20 years), high rainfall and stable temperature suited to vigorous growth in biomass than CS (40.03 Mg C ha^{-1}) observed in present study under subtropical climate of India with a tree density of 156 ha^{-1} in NW Himalaya in 25 years (Rathore, et al. 2021).

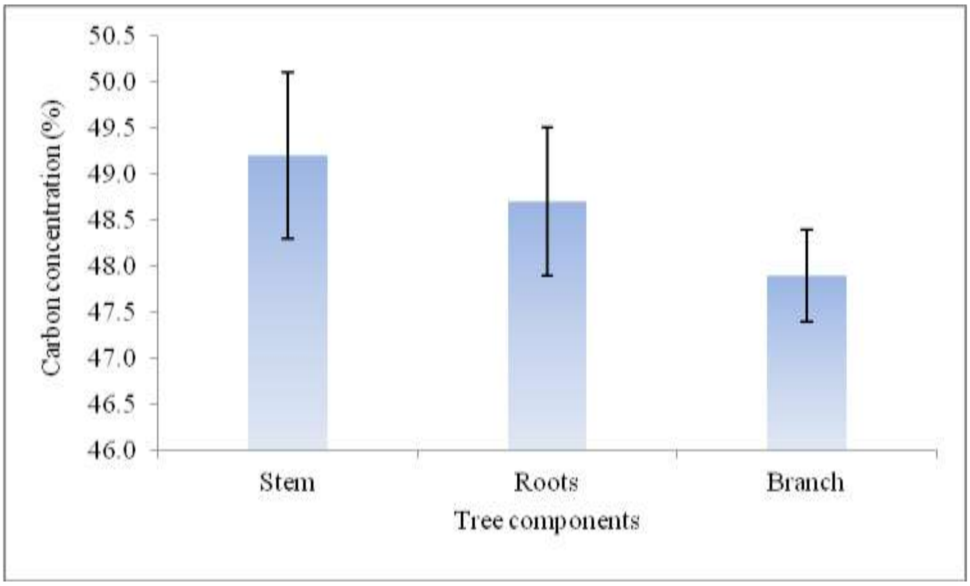

Fig. 2 Carbon concentration in different components of mango grown on degraded land

Table 7 Carbon stocks of different tree components of mango cultivars (Mg ha^{-1}) on degraded lands

Cultivars	Stem	Branch	Above ground	Below ground	Total	Carbon sequestration rate (Mg C ha^{-1} yr^{-1})
Mallika	22.49	6.67	29.16	10.87	40.03	1.60
Dashehari	20.12	5.75	25.87	10.51	36.38	1.46
Langra	21.17	5.99	27.16	9.88	37.04	1.48
B. green	20.85	6.04	26.89	10.55	37.44	1.50
Ramkela	20.27	5.45	25.72	9.53	35.25	1.41
Amrapali	20.00	5.30	25.30	8.97	34.27	1.37

Total carbon stock (TCS) includes biomass C plus soil C (30 cm depth) in each mango cultivar varied significantly (Table 8). The maximum TCS (76.00 Mgha^{-1}) was recorded in Mallika cultivar which was 6.7 to 17.9% higher over other mango cultivars. Soil organic carbon (SOC) is not a tradable output but important for plant growth and was measured at 30 cm soil depth. SOC was 3.3% to 22.6% higher than all mango cultivars after 25 years in 2020 than establishment year (1995). The biomass C was higher than SOC among all cultivars of mango. The highest TCSs under Mallika may be attributed to bigger tree architecture, more canopy spread, more litter yield, etc over other mango cultivars. The litter fall increased SOC which reduced bulk density by increasing organic matter in the system for moisture conservation. Previous workers also reported that higher litter returned to soil improved carbon stock (CS) in fruit based AFSs (Yadav et al. 2015; Rathore et al. 2021). Similarly, Mallika recorded maximum equivalent CO_2 (278.67 Mg ha^{-1}) and minimum TCS (236.35 Mg ha^{-1}) in Amrapali in 25 years old mangos (Table 8). CO_2 mitigation by plants is directly related to biomass production of trees. Biomass and soil depth were positively correlated with

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tree and soil carbon, respectively. This relationship indicated that more biomass has more CS in the trees and similarly, more soil depth stored more soil carbon in the system. CSs either in the tree or in the soil sequester atmospheric CO_2 and reducing atmospheric temperature as presently CO_2 concentration (400 ppm) is main cause of global warming. The soil is a bigger reservoir of carbon after ocean in the ecosystem. Globally CS in soil exceeded than vegetation by a factor of five (IPCC 2000). Therefore, soil C is important when the potential for sequestration and long-term storage is considered (Takimoto et al. 2008).

Table 8 Carbon stocks of trees and soils as well as CO_2 mitigation potential of different mango cultivars on degraded lands

Cultivars	Carbon stock (Mg ha^{-1})			CO_2 mitigation (Mg ha^{-1})		
	Tree stock	Soil stock	Total	Tree stock	Soil stock	Total
Mallika	40.03	35.97	76.00	146.74	131.89	278.63
Dashehari	36.38	34.81	71.19	133.39	127.64	261.03
Langra	37.04	34.38	71.42	135.81	126.06	261.87
B. green	37.44	30.06	67.5	137.28	110.22	247.50
Ramkela	35.25	29.33	64.58	129.25	107.54	236.79
Amrapali	34.27	30.19	64.46	125.66	110.70	236.35

Economic viability

Economic analysis of mango cultivars [net present value (NPV), benefit cost ratio (BCR) and payback period (PBP)] had clearly revealed that mallika cultivar was most profitable cultivar among mango cultivars. This was evident from Table 9 that highest NPV (32,068 USD) was observed in Mallika followed by Amrapali (26,795 USD) and minimum NPV (20,514 USD) with Bombay Green during 25 years of orchard life. The NPV of Mallika cultivar was 19.68 to 56.32% higher than all other mango cultivars. Similarly, benefit-cost ratio (BCR) was also highest with Mallika (3.26), which was 14.39 to 63.3% higher over all mango cultivars. Likewise, the payback period (PBP) was lowest (5.0 years) with Mallika cultivar which was 9.0 to 28.57% lesser as compared to other cultivars. The economic evaluation of mango cultivars indicated that all cultivars were economically profitable on degraded lands as these cultivars were having positive NPVs >20514 USD, BCRs > 1.0 and PBP (5-7 years). Mallika cultivar of mango had significantly highest NPV and BCR, and minimum PBP over all other cultivars due to regular fruiting, more pulp content (73.73%), bigger fruit weight (382.0 g) and better suitability (maximum canopy and root production). Moreover, Mallika is suitable for consumption as well as preferred by pulp industry for processing purpose with higher economic benefits over other cultivars (Rathore et al. 2013, 2020, Singh 1978; Negi 2000). Besides fruit yield, Mallika added more nutrients to the soil by adding more bio-litter which improved soil fertility, soil moisture retention, restore soil microbial population and rehabilitation of degraded lands (Saroj et al. 1994).

Table 9 Economic evaluation of mango cultivars grown on degraded lands (1995-2020)

Economic parameter (ha^{-1})	Mallika	Amrapali	Ramkela	Langra	Dashehari	Bombay green
Net present value (USD*)	32,068	26,795	24,990	22,800	20,926	20,514
B:C ratio	3.26	2.85	2.45	2.32	2.14	2.00
Payback period (years)	5.0	5.0	6.0	6.0	7.0	7.0

CONCLUSION

Experimental studies in six mango cultivars were conducted for 25 years (1995-2020) on degraded lands at ICAR-IISWC, Dehradun. Mango trees added bio-litter and below ground parts (roots) in the form of organic carbon in the soil after decomposition, thereby improving soil fertility of degraded lands. Plantation of fruit trees in this regards not only provide environmental security but also extended nutritional security to the people. A 25 years mango plantation (Mallika) was able to produce fruit yield as high as 14.20 tha^{-1} and locked 40.03 Mg C ha^{-1} (1.60 tha^{-1} yr^{-1}) thereby sequestering 146.78 Mg ha^{-1} of equivalent CO_2 from the atmosphere. It aided carbon sequestration strategies and environmental security besides providing nutritional security. The economic benefits were substantial as cost benefit ratio varied from 2.0 to 3.26 in different mango cultivars thereby supplementing the income of farmers. Based on these observations, it is concluded that mango cultivars can be grown successfully in degraded lands supported by appropriate natural resource management technologies in subtropical climate. Thus, mango cultivation on degraded lands proved highly productive, remunerative and ecologically sound preposition for rehabilitating such lands.

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