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RESEARCH PAPER

Effect of artificially simulated moisture regimes on growth attributes of different *Eucalyptus* clones in sub-tropics of north-western India

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Abstract

Eucalyptus clones respond differentially under variable moisture regimes with considerable differences in net primary production due to changed rates of photosynthesis which eventually influence plant growth attributes due to change in stomatal conductance and transpiration rate. We studied the growth attributes of five different *Eucalyptus* clones (PE-17, C-2045, PE-11, PE-1 and C-413) in response to varying moisture regimes viz. optimal (100% Cumulative Pan Evaporation; CPE_{100}), sub-optimal (75% CPE; CPE_{75}) and super-optimal (125 and 150% CPE; $CPE_{125/150}$). Plant establishment under CPE_{100} resulted in significantly ($p < 0.05$) higher plant height (by ~ 8.9%), collar diameter (by ~ 9.3%) and number of branches plant^{-1} (by ~ 63.6%) at 90 days after their establishment, compared with those established under CPE_{75}. Conversely, there was a non-significant ($p < 0.05$) difference in number of roots plant^{-1} as well as root length of *Eucalyptus* clones at 120 days after establishment under CPE_{75} and CPE_{100}. However, these root growth attributes were significantly decreased under super-optimal moisture ($CPE_{125\text{-}150}$; by ~ 30.2 to 37.5% for number of roots plant^{-1} and ~ 15.0 to 17.6% for root length) as compared to those under optimal moisture regime (CPE_{100}). Regardless of the moisture regimes, PE-1 clone has significantly higher collar diameter, number of branches/roots plant^{-1}, and dry branches + leaves and roots biomass, compared with other clones. The CPE_{100} helped increase the net primary production significantly in different components viz. dry biomass of branches + leaves (by ~ 25.1%), stems (by ~ 24.1%) and roots (by ~ 32.2%), compared with CPE_{75}. The branches + leaves biomass of *Eucalyptus* was significantly related to the stems biomass (0.9096**; $p < 0.01$). The rate of photosynthesis was significantly decreased by ~ 56.6 to 80.6% under super-optimal ($CPE_{125\text{-}150}$), compared with under optimal (CPE_{100}) moisture regime. Similarly, the stomatal conductance was decreased by ~ 46.5 to 71.8% under $CPE_{125–150}$ than CPW_{100}. The stomatal conductance increased with increased rates of photosynthetic activity ($R^2 = 0.888$), regardless of the clone and moisture regime. The transpiration rate of *Eucalyptus* clones was increased by ~ 58.2% under CPE_{100} than under CPE_{75}, but was decreased significantly (by ~ 34.9 to 79.6%) with increase in moisture regime from CPE_{100} to $CPE_{125–150}$. Therefore, it can be concluded these *Eucalyptus* clones has considerable potential for increased productivity at CPE_{100}; although PE-1 outperformed based on growth attributes and rates of photosynthesis, transpiration and stomatal conductance to yield higher net primary production.

Keywords Stomatal conductance · Transpiration rate · Net primary production · Moisture regimes

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Introduction

Eucalyptus, a native of Australia was brought to India in the late eighteenth century. At present, ~ 600 to 700 *Eu Eucalyptus* species exists across the globe (Teketay 2000; Rassaeifar et al. 2013). Eucalypts are extremely productive by easier flexibility to dry environment, infertile soils and could therefore efficiently be utilized for a productive land-use of degraded landscapes which do not support agriculture any longer (Li et al. 2015; Avtar-Singh et al. 2022; Madiwalar et al. 2022). *Eucalyptus* species has high contribution towards the restoration of lands and water logged landscapes (Avtar-Singh et al. 2022; Baljit-Singh et al. 2023). Although, *eucalyptus* plantations are often condemned due to their high water consumption, but recent research in efficiently managed plantations highlighted their overwhelming significance for the restoration of environment and landscapes (Poore and Fries 1985; White et al. 1995; Casson 1997; Bilal et al. 2014). *Eucalyptus* species are known for high water requirements (5324 L year^{-1}) therefore, notwithstanding the water consumption characteristics, their cultivation alongside the waterlogged landscapes rather has high potential for land reclamation and land-use change to productive landscapes (Avtar-Singh et al. 2022; Baljit-Singh et al. 2023).

In India, the majority of *eucalyptus* plantations on government, forest, farm lands, and community lands and along road, rail and canal strips are of seed origin, however, several private and government organizations and/or research institutes a well as paper mills from South India initiated the tree improvement programme on *Eucalyptus* clones (Kulkarni 2002; Lal et al. 1997, 2006). In north-western India, tree improvement programme initiated in late 1990s with the progenies of trees from Australia, Punjab, Tamil Nadu, Chhattisgarh and West Bengal (Dhillon and Singh 2010; Dhillon et al. 2011). It is strongly believed that the annual replacement of 5–10% of existing clones is required to maintain genetic diversity while sustainably maintaining the productivity of vegetative propagated tree species (Zsuffa 1983). Therefore, there is a need to develop new clones with enhanced productivity, increased tolerance to insect-pests and adaptability to extremes of moisture conditions (Varghese et al. 2008).

In India, pulpwood shortage has formed the need for rapidly growing species and has become the most important reason to plant *Eucalyptus* in large scale plantations (Shiva et al. 1981). The achievements in genetic improvement of forest tree species are less spectacular than those in agricultural crops, because the forest tree species are difficult to breed, has longer generation times and are prone to out breeding. The farmer's always has preference for short duration fast growing species, because of market uncertainties and the desire for early returns, the clonal *Eucalyptus* are gaining ground across the globe (Delwaulle 1985; Campinhos and Ikemori 1977; Kulkarni 2004; Lal 2008). Additionally, *Eucalyptus* plantation has large potential for carbon (C) sequestration in soils as well as in tree biomass (Avtar-Singh et al. 2022; Madiwalar et al. 2022), the potential of which depends upon tree stand age (Claus and George 2005; Borja et al. 2008; Du et al. 2015). The forest ecosystems comprised ~ 7% of the world's forest area (increased by ~ 5 Mha year^{-1} during 2005–10), with a significant impacts on global C cycling (FAO 2010; Zhang et al. 2011; Chen et al. 2013; Gonzalez et al. 2013). The C fluxes are thought to be considerably influenced by topography, climate, soil characteristics, tree species, soil management regime, land-use history as well as by and stand age (Du et al. 2015; Fahey et al. 2010; Paul et al. 2002; Deluca and Boisvenue 2012). The *Eucalyptus grandis* cultivars may sequester more than 10 Mg C ha^{-1} year^{-1} as a short rotation woody crops (Rockwood et al. 2022), and could therefore, serve as most viable option for C mitigation.

The atmospheric air easily exchanges within the soil air replenishing oxygen (O_2) in a continuous process. Conversely, waterlogging leads to the development of saturated moisture regimes, thereby, causing reduced O_2 concentration, a state of hypoxia in soils (Ahmed et al. 2013). The growth and development of plants under water-logged environments is significantly influenced by the decreased O_2 levels in soil rhizosphere (Christianson et al. 2010). The exploitation of bio-remediation potential of *Eucalyptus* under water-logged landscapes depends up on evapotranspiration (Jeet-Ram et al. 2011). Trees act as biological drainage agents which help lower water table depths and are considered very simple as well as energy saving measures (Avtar-Singh et al. , 2022), and forms the basis of a 'propoor' approach for enhancing farm income of poor farmers, who otherwise might leave their lands barren. The moisture stress (excess or paucity) makes interaction relationships of tree growth both appropriate and complex and the stressors can intensify, overlap and ameliorate the impact of the stress (Osmond et al. 1987). The tree species stereotypically experience a wide range of resource limitations which eventually impacts its productivity, through their interactive influence on rate of photosynthesis and growth (Vellini et al. 2008). It has been reported that defoliation of *E. globulus* usually persuades an increased rate of net photosynthesis (Pinkard et al. 2007; Quentin et al. 2010) as well as the transpiration per unit leaf area due to increased hydraulic conductance (Quentin et al. 2011). Conversely, drought condition exerts negative impacts on *E. globulus* e.g. reductions in transpiration and canopy conductance (O'Grady et al. 2008), decreased leaf water potential (O'Grady et al. 2008) and the rate of stomatal conductance (Pereira et al. 1989).

To date there is a dearth of requisite information on response of *Eucalyptus* species on the interactive effects of

how low and excess moisture availability influences defoliation and physiological response in different environments. It is well known that water transport and rate of net photosynthesis in trees are controlled by the hydraulic conductance of the pathway from the soil to the leaf (Tyree and Ewers 1991). In north-western India, there are several *Eucalyptus* clones which are cultivated across wide range of environments with differential response towards abiotic stresses of soil salinity and water-lodging (Avtar-Singh et al. 2022). There is a little information on effect of moisture regimes on tree growth attributes in relation to rate of photosynthesis and transpiration which are signifintly governed by stomatal conductance.

Therefore, to better understand the growth, development and hydrological impact of a *Eucalyptus* plantation, it is necessary to understand the influence of variable moisture regimes. Earlier research remains focused on studying the response of different *Eucalyptus* clones in saline water-logged environments, but lacks information on response of clones due to changed photosynthetic activity in relation to stomatal and hydrological conductance. We compared the differential impacts of sub-optimal, optimal and super-optimal moisture regimens on growth attributes and net primary productivity in various above-and below-ground biomass components in relation to rates of photosynthesis, stomatal and transpiration rates of five different *Eucalyptus* clones in sub-tropical north-western India.

Materials and methods

Description of study region

An experiment was established in main experimental area of the Department of Forestry & Natural Resources, Punjab Agricultural University (PAU), Ludhiana, Punjab (India) (30° 56′ N and 75° 52′ E). The study region has a typical sub-tropical climate, with hot, wet summers and cold dry winters. Annual mean rainfall is ~ 760 mm, ~ 80% of which received in *monsoon* season extending between July and September.

Details of pot experiment

The rooted softwood cuttings of five clones viz. PE-17, C-2045, PE-11 (Australia seed centre, progeny no. 13547/JD1043), PE-1 and C-413 (ITC, Bhadrachalam Paper Mills) were shifted in polythene bags and kept there for two months. Ten plants of each clone were planted in the field in May-2015 in the pots. The clones were planted in completely randomized design (CRD) to accommodate four moisture regime treatments with three replications. The moisture regimes of sub-optimal, optimal and super-optimal were simulated at 75, 100, 125 and 150% of the Cumulative Pan Evaporation (CPE) reading (referred as CPE_{75}, CPE_{100}, CPE_{125} and CPE_{150}). The data on CPE were obtained from the School of Climate Change and Agricultural Meteorology at PAU, Ludhiana. The volume of irrigation water equivalent to simulated moisture regimes was estimated using Eq. 1.

$$\begin{aligned} &Volume\ of\ irrigation\ water\ under\ optimal\ moisture\ regime\left(CPE_{100};inL\right) \\ &= Area\left(in\ m^2\right) \times CPE(in\ mm) \end{aligned} \tag{1}$$

Therefore, the amount of water to simulate CPE_{75}, CPE_{125} and CPE_{150} were estimated as 0.75 × volume of water in CEP_{100}, 1.25 × volume of water in CEP_{100} and 1.50 × volume of water in CEP_{100}, respectively. The amount of estimated water (as per treatment) was applied at an interval of two days. The fertilizer N, P and K were applied as per recommendations of the PAU, Ludhiana.

Growth parameters

Plant growth parameters were recorded in February-2016. The plant height (ground level to the tip of the main leading shoot) of each *Eucalyptus* clones was measured at 60 and 90 days after planting using wooden scale (Madiwalar et al. 2022). The collar diameter was measured with vernier caliper at the collar region approximately five cm from the base (expressed in cm). The number of branches emerged from the main shoot were manually counted all through the length of the plant from its base to the tip. The number of roots/plant were manually counted and root length was measured using scale (expressed in cm). For measuring root length, the main root was considered and its length was recorded from base of stem (where the roots arise) up to the tip of the root. The plants of each clone were taken out of the pots after 90 days, and the biomass was partitioned as branches + leaves, stems and roots. The sub-samples (branches + leaves, stems and roots) of each clone were weighed as such for recording their fresh weight (g $plant^{-1}$). These sub-samples were dried in an oven at 60 ± 5 °C till the samples were attained constant weight for recording the dry weight (g $plant^{-1}$).

Photosynthesis, transpiration and stomatal conductance

The data on photosynthesis, transpiration and stomatal conductance was recorded in July 2016 using the portable photosynthesis system (Model LICOR-6400). The data on these variables were recorded from the sixth leaf from the top

of plant. The carbon dioxide (CO_2) was fixed at 400 ppm, whereas Quantum Flux value was kept constant at 1000.

Biomass C sequestration in above-ground biomass

The estimation of C sequestration in dry above-and below-ground components was based on C content in various components of *Eucalyptus* viz. 46.6% in stem, 44.7% in twigs + leaves and branches and 46.9% in roots (Dagar et al. 2016).

Statistical analysis

The data on the growth parameters, biomass and rates of photosynthesis, stomatal conductance and transpiration were statistically analyzed using analysis of variance (ANOVA) technique in completely randomized design (CRD) (Cochran and Cox 1957) using SPSS for Windows 16.0 (SPSS Inc., Chicago, USA). Least significant difference (LSD) test values were tested at 5% ($p < 0.05$) level of probability. The correlation matrix was developed to establish relationship between different variables using SPSS InC., Chicago, U.S.A.), and the relationships significant at $p < 0.05$ and $p < 0.01$ were elucidated using * and ** in the text.

Results

Agronomic attributes of Eucalyptus clones under varying moisture regimes

Mean plant height of different *Eucalyptus* clones decreased significantly ($p < 0.05$) with increased moisture regime at 60 and 90 days after the establishment (Table 1). At CPE_{100}, the optimal moisture regime, mean height at 60 days after establishment was significantly higher (by ~ 16.1%) than at $CPE_{125/150}$. There was a non-significant ($p < 0.05$) difference in plant height at sub-optimal (CPE_{75}) and optimal (CPE_{100}) moisture regimes, regardless of the *Eucalyptus* clone. At 60 days after sapling establishment in the field, clone C-413 exhibited a significantly higher plant height by ~ 17.2, 25.7 and 11.4% than PE-17, C-2045 and PE-1, respectively. The response of *Eucalyptus* clones towards increased moisture regimes at 90 days followed a similar trend to that at 60 days after sapling establishment. The mean height of C-413 was

Table 1 Plant growth attributes of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India

Moisture level	Plant height (cm) at 60 days						Plant height (cm) at 90 days					
	PE-17	C-2045	PE-11	PE-1	C-413	Mean	PE-17	C-2045	PE-11	PE-1	C-413	Mean
CPE_{75}	91.3	85.0	88.8	77.5	97.5	88.0	102.5	96.3	98.8	90.0	107.5	99.0
CPE_{100}	82.5	80.0	98.8	82.5	100.0	88.8	101.3	96.3	120.0	100.0	121.3	107.8
CPE_{125}	68.8	61.3	71.3	86.3	93.8	76.3	73.8	63.8	76.3	98.8	100.0	82.5
CPE_{150}	71.3	66.3	86.3	83.8	76.3	76.8	73.8	67.5	88.8	88.8	80.0	79.8
Mean	78.4	73.1	86.3	82.5	91.9		87.8	80.9	95.9	94.4	102.2	
LSD ($p < 0.05$)	Moisture level = 6.8; Clones = 7.6, Moisture level × clones = 15.2						Moisture level = 9.0; Clones = 10.0; Moisture level × clones = NS					
	Collar diameter (mm) at 90 days						Number of branches plant^{-1} at 90 days					
CPE_{75}	5.1	4.9	5.4	6.4	5.1	5.4	19.1	19.3	24.9	22.8	20.8	21.4
CPE_{100}	5.6	4.6	6.6	6.8	5.9	5.9	32.0	29.4	37.6	47.4	28.4	35.0
CPE_{125}	4.5	3.6	4.9	7.6	5.2	5.1	8.7	7.5	19.0	50.8	20.4	21.3
CPE_{150}	5.2	4.8	5.8	7.3	4.7	5.6	17.5	12.6	16.9	45.9	21.6	22.9
Mean	5.1	4.5	5.7	7.0	5.2		19.3	17.2	24.6	41.7	22.8	
LSD ($p < 0.05$)	Moisture level = NS; Clones = 0.72, Moisture level × clones = NS						Moisture level = 1.7; Clones = 1.8, Moisture level × clones = NS					
	Number of roots plant^{-1} at 120 days						Root length (cm) at 120 days					
CPE_{75}	9.8	9.5	6.8	11.5	12.3	10.0	29.8	22.8	25.0	26.0	27.3	26.2
CPE_{100}	7.0	9.0	10.3	13.8	8.0	9.6	26.8	21.0	29.3	30.0	26.5	26.7
CPE_{125}	7.3	5.0	5.8	7.8	7.8	6.7	18.5	17.8	23.3	27.0	26.8	22.7
CPE_{150}	5.0	5.3	6.8	6.3	6.8	6.0	23.5	14.3	27.0	22.8	22.5	22.0
Mean	7.3	7.2	7.4	9.8	8.7		24.6	18.9	26.1	26.4	25.8	
LSD ($p < 0.05$)	Moisture level = 1.8; Clones = 2.0, Moisture level × clones = NS						Moisture level = 2.8; Clones = 3.2, Moisture level × clones = NS					

increased significantly higher by ~ 16.4, 26.3 and 8.3, respectively over PE-17, C-2045 and PE-1 clones. Similarly, mean height was increased by ~ 30.7 and 35.1%, respectively at optimal (CPE_{100}) than at super-optimal (CPE_{125} and CPE_{150}, respectively) moisture regimes. These results revealed a non-significant effect of moisture regimes on collar diameter of *Eucalyptus* clones. The collar diameter at 90 days after plant establishment was significantly higher for PE-1 and the lowest for C-2045, whilst the PE-17, PE-11 and C-413 clones in-between and did not differ significantly.

The *Eucalyptus* clones differ significantly at varying moisture regimes for number of branches plant^{-1}. The clone PE-1 has significantly higher number of branches plant^{-1} by 116, 142, 70 and 83% higher than the PE-17, C-2045, PE-11 and C-413, respectively. The number of branches plant^{-1} was significantly increased by increasing the moisture regime from CPE_{75} to CPE_{100}. However, number of branches plant^{-1} was decreased significantly by ~ 64.4 and 52.8%, respectively at CPE_{125} and CPE_{150} than at CPE_{100}. Similarly, the number of roots plant^{-1} was significantly higher for PE-1 clone by 32.4–36.1% than others except for C-413. There was a non-significant difference in number of roots plant^{-1} for C-413 and PE-1 (data pooled for different moisture regimes). The increase in moisture regime from CEP_{100} to CPE_{125} and CPE_{150} resulted in a significant decrease in number of roots plant^{-1} by 43.3 and 59.9%, respectively. Regardless of the moisture regime, root length was significantly lower for C-2045 by ~ 23.2 to 28.4% than other *Eucalyptus* clones. There was a significant decrease in root length of *Eucalyptus* plants by ~ 17.6 to 21.4% with increase in moisture regimes higher than CPF_{100}. The interaction effect of moisture regimes vs. *Eucalyptus* clones at 90 days after sapling establishment was statistically non-significant.

Plant biomass of Eucalyptus clones under varying moisture regimes

These results revealed a significant change in fresh and dry weight biomass of different *plant* components for studied clones established at varying moisture regimes (Table 2). These results revealed significantly lower net primary production as branches + leaves, stems as well as roots biomass (both fresh and dry) for C-2045, whilst significantly higher for PE-1 clone. However, there was a non-significant

Table 2 Fresh and dry weight attributes of above-and below-ground biomass components of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India

Moisture level	Fresh weight of branches + leaves biomass (g plant^{-1})						Dry weight of branches + leaves biomass (g plant^{-1})					
	PE-17	C-2045	PE-11	PE-1	C-413	Mean	PE-17	C-2045	PE-11	PE-1	C-413	Mean
CPE_{75}	38.5	30.6	33.8	54.8	47.9	41.1	24.8	19.1	24.4	36.0	31.3	27.1
CPE_{100}	41.5	31.7	71.7	67.3	62.5	54.9	24.5	19.6	48.5	40.3	36.5	33.9
CPE_{125}	13.3	11.0	28.7	80.5	41.3	34.9	7.7	5.9	16.7	46.0	22.6	19.8
CPE_{150}	16.6	11.7	31.4	55.1	17.6	26.5	9.6	6.4	17.8	30.6	10.0	14.9
Mean	27.5	21.3	41.4	64.4	42.3		16.6	12.8	26.8	38.2	25.1	
LSD ($p < 0.05$)	Moisture level = 11.4; Clones = 12.7, Moisture level × clones = NS						Moisture level = 11.4; Clones = 12.7; Moisture level × clones = NS					
	Fresh weight of stem biomass (g plant^{-1})						Dry weight of stem biomass (g plant^{-1})					
CPE_{75}	19.1	15.5	21.0	19.5	21.7	19.4	10.6	8.4	12.1	11.1	11.8	10.8
CPE_{100}	18.3	18.1	30.7	26.0	25.8	23.8	10.7	9.5	18.9	13.4	14.4	13.4
CPE_{125}	6.9	5.3	12.8	28.2	18.6	14.3	4.3	3.4	7.4	16.8	12.1	8.8
CPE_{150}	7.1	9.1	15.8	22.4	9.4	12.8	4.3	5.7	9.6	12.9	5.9	7.6
Mean	12.8	12.0	20.1	24.0	18.9		7.5	6.7	12.0	13.5	11.0	
LSD ($p < 0.05$)	Moisture level = 5.0; Clones = 5.6, Moisture level × clones = NS						Moisture level = 2.8; Clones = 3.2, Moisture level × clones = NS					
	Fresh weight of root biomass (g plant^{-1})						Dry weight of root biomass (g plant^{-1})					
CPE_{75}	19.1	19.3	24.9	22.8	20.8	21.4	13.6	13.7	16.8	13.7	15.2	14.6
CPE_{100}	32.0	29.4	37.6	47.4	28.4	35.0	17.0	15.7	22.6	25.1	16.5	19.3
CPE_{125}	8.7	7.5	19.0	50.8	20.4	21.3	5.4	4.9	11.4	31.1	13.4	13.3
CPE_{150}	17.5	12.6	16.9	45.9	21.6	22.9	7.7	5.7	7.6	20.9	6.9	9.7
Mean	19.3	17.2	24.6	41.7	22.8		10.9	10.0	14.6	22.7	13.0	
LSD ($p < 0.05$)	Moisture level = 9.6; Clones = 10.7, Moisture level × clones = NS						Moisture level = 5.2; Clones = 5.8, Moisture level × clones = NS					

difference in these biomass components amongst the PE-11 and C-413 clones. The fresh biomass + leaves weight of PE-1 clone was significantly higher by ~ 134.2, 202.3, 55.6 and 52.2% higher than PE-17, C-2045, PE-11 and C-413 clones. Similarly, the dry branches + leaves biomass weight of PE-1 clone was significantly higher by 130.1, 198.4, 42.5 and 52.2%, respectively. The fresh branches + leaves biomass was significantly higher at CPE_{100} by ~ 33.6 than at CPF_{75}. Similarly, the dry branches + leaves biomass was significantly increased by ~ 25.1% at CPE_{100} over CPE_{75}. However, the fresh branches + leaves biomass was significantly decreased by ~ 57.3 and 107.2% with increased moisture regime from CPF_{100} to CPF_{125} and CPF_{150}, respectively. The corresponding decreases however for dry branches + leaves biomass was ~ 71.2 and 127.5%, respectively over CPF_{100}. The stems biomass (fresh and dry) was significantly higher for PE-1 clone (by ~ 27 to 99.8% fresh weight and ~ 23.1 to 101.5% dry weight) than the PE-17, C-2045 and C-413 clones. The fresh and dry stems biomass weight was significantly increased by ~ 22.7 and 24.1% respectively with increase in moisture regime from CPF_{75} to CPF_{100}. However, with further increase in moisture regime at CPF_{125} and CPF_{150}, there was a significant decrease in fresh stems biomass weight by ~ 66.4 and 85.9% and dry biomass by ~ 52.3 and 76.3%, respectively over CPF_{100}. The fresh roots biomass weight was significantly higher for PE-1 by ~ 116.1, 142.4, 69.5 and 83.0% than PE-17, C-2045, PE-11 and C-413 clones, respectively. However, the dry root biomass weight was higher for PE-1 clone by ~ 108.3, 127.1, 55.5 and 74.6%, respectively for these clones. Similar to branches + leaves and stems biomass weight, the fresh and dry roots biomass weight was significantly increased by 63.6 and 32.2%, respectively with increase in moisture regime from CPF_{75} to CPF_{100}. Nonetheless, there was a significant decrease of ~ 64.3 and 52.8% for fresh, and ~ 45.1 and 99.1% for dry roots biomass weight with increase in moisture regime rom CPF_{100} to CPF_{125} and CPF_{150}, respectively (Table 2). There was a linear significant relationship between fresh and dry weight biomass of different *Eucalyptus* plant components at varying moisture regimes (Eqs. 2–4) (Fig. 1).

$$\text{Dry branches + leaves biomass } (\text{g plant}^{-1}) = 0.6154(\text{fresh branches + leaves biomass, g plant}^{-1}) - 0.3173;\ R^2 = 0.9739\ **\ (p < 0.01), \quad (2)$$

$$\text{Dry stems biomass } (\text{g plant}^{-1}) = 0.5608(\text{fresh stems biomass, g plant}^{-1}) + 0.3142;\ R^2 = 0.9731\ **\ (p < 0.01), \quad (3)$$

$$\text{Dry roots biomass } (\text{g plant}^{-1}) = 0.5322(\text{fresh roots biomass, g plant}^{-1}) + 0.8697;\ R^2 = 0.8701\ *\ (p < 0.05). \quad (4)$$

The branches + leaves biomass of *Eucalyptus* plants was linearly related to their stems biomass weight (Fig. 2). The relationship between these variables could best be described by a positive significant relationship (Eq. 5). Root biomass

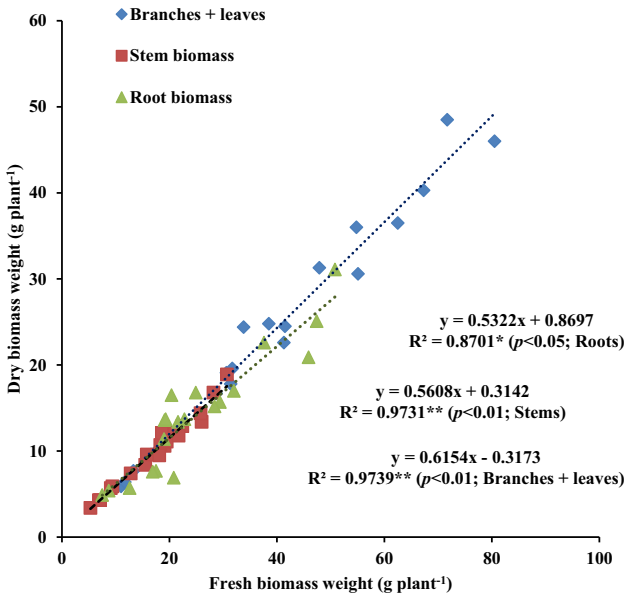

Fig. 1 Relationship between fresh and dry branches + leaves, stems and roots biomass of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India. Data pooled for different clones tested under variable moisture regimes

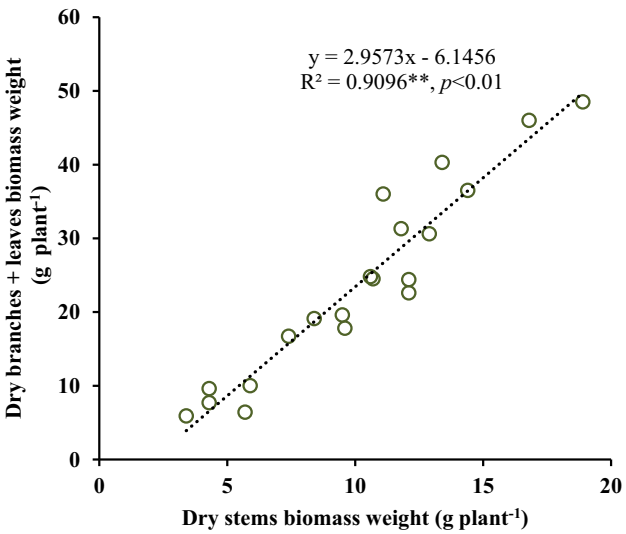

Fig. 2 Relationship between dry stems and branches + leaves biomass weight of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India. Data pooled for different clones tested under variable moisture regimes (g plant^{-1})

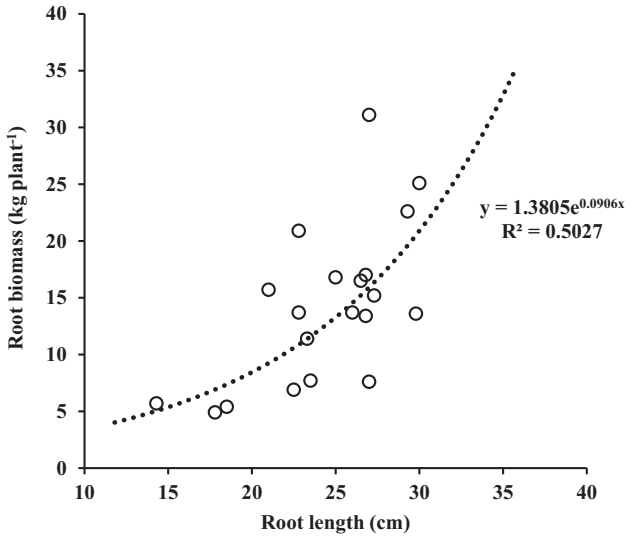

Fig. 3 Relationship between root length and root biomass of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India. Data pooled for different clones tested under variable moisture regimes

weight exhibited an increase with increase in root length of *Eucalyptus* plants (Eq. 6) (Fig. 3).

$$\text{Dry branches} + \text{leaves biomass weight}\left(\text{g plant}^{-1}\right) = 2.9573\left(\text{dry stem biomass weight; g plant}^{-1}\right) - 6.1456; R^2 = 0.9096 ** (p < 0.01), \quad (5)$$

$$\text{Root biomass weight}\left(\text{kg plant}^{-1}\right) = 1.3805e^{0.0906(\text{root length, cm})}; R^2 = 0.5027. \quad (6)$$

Photosynthesis, stomatal conductance and transpiration rate

Eucalyptus clones respond significantly towards varying moisture regimes for photosynthesis, stomatal conductance and transpiration rate (Table 3). Amongst the different clones compared, PE-1 has significantly higher, C-2045 has lowest photosynthesis rate, whilst the others in-between. As compared with the C-413 clone, PE-1 has ~ 23.5% higher photosynthesis rate. These results showed non-significant difference in photosynthesis rate at CPE_{75} and CPE_{100}, however, it decreased significantly by ~ 56.6 and 80.6%, respectively with increased moisture regime at CPE_{125} and CPE_{150}. The stomatal conductance rate was significantly lower for PE-17, and the highest for PE-1. However, there was a

Table 3 Photosynthesis, stomatal conductance and transpiration rate of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India

Moisture level	Photosynthesis (μmol CO_2 m^{-1} s^{-1})					
	PE-17	C-2045	PE-11	PE-1	C-413	Mean
CPE_{75}	11.5	11.3	13.3	13.3	11.9	12.3
CPE_{100}	13.7	12.8	13.5	12.5	12.3	12.9
CPE_{125}	4.9	3.2	4.5	10.5	4.8	5.6
CPE_{150}	1.4	0.8	3.2	3.8	3.3	2.5
Mean	7.8	7.0	8.6	10.0	8.1	
LSD ($p < 0.05$)	Moisture level = 0.82; Clones = 0.92, Moisture level × clones = NS					
	Stomatal conductance (mol H_2O m^{-2} s^{-1})					
CPE_{75}	3.50	3.69	3.89	3.89	3.76	3.75
CPE_{100}	3.65	4.01	4.43	4.57	4.28	4.19
CPE_{125}	1.57	2.11	2.56	2.50	2.49	2.24
CPE_{150}	0.75	0.73	1.55	1.79	1.09	1.18
Mean	2.37	2.63	3.11	3.19	2.90	
LSD ($p < 0.05$)	Moisture level = 0.41; Clones = 0.46, Moisture level × clones = NS					
	Transpiration rate (mmol H_2O m^{-2} s^{-1})					
CPE_{75}	3.80	3.69	4.07	4.07	3.26	3.78
CPE_{100}	5.95	5.32	5.64	6.72	6.26	5.98
CPE_{125}	3.05	2.30	4.02	6.39	3.70	3.89
CPE_{150}	0.71	0.64	1.19	2.60	0.96	1.22
Mean	3.38	2.99	3.73	4.94	3.55	
LSD ($p < 0.05$)	Moisture level = 0.65; Clones = 0.73, Moisture level × clones = NS					

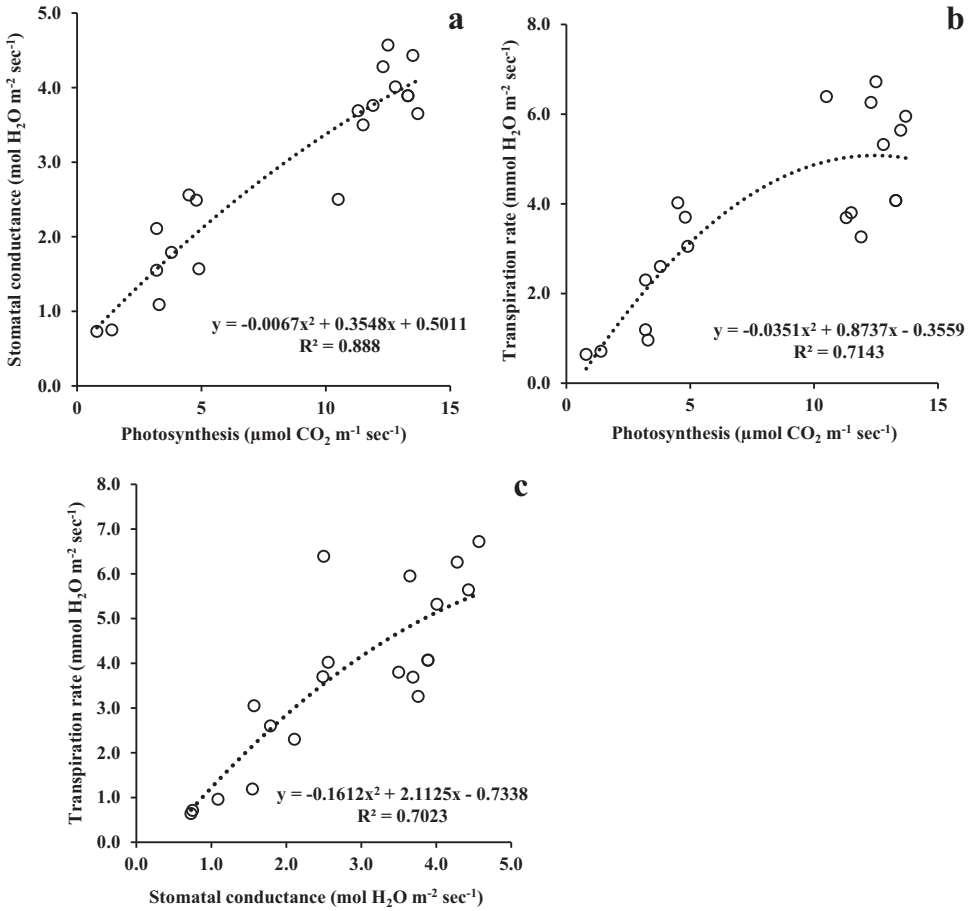

Fig. 4 Relationship between photosynthesis rate (**a**), stomatal conductance (**b**) and transpiration rate (**c**) of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India. Data pooled for different clones tested under variable moisture regimes

non-significant difference in stomatal conductance amongst the PE-11 and PE-1 clones. The stomatal conductance was significantly decreased by ~ 46.5 and 71.8%, respectively with increase in moisture regime from CPW_{100} to CPE_{125} and CPE_{150}. These results revealed that increased photosynthetic activity resulted in increased rate of stomatal conductance. Figure 4a best describe the relationship between photosynthesis rate and stomatal conductance of different *Eucalyptus* clones (Eq. 7).

$$\begin{aligned}&\text{Stomatal conductance}\left(\text{mol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)\\&=-0.0067\left(\text{Photosynthesis; }\mu\text{mol CO}_2\text{m}^{-1}\ \text{s}^{-1}\right)^2\\&\quad+0.3548\left(\text{Photosynthesis; }\mu\text{mol CO}_2\text{m}^{-1}\ \text{s}^{-1}\right)\\&\quad+0.5011;\ \text{R}^2=0.888.\end{aligned}\tag{7}$$

Similar to the photosynthesis and stomatal conductance rate, transpiration followed a similar trend in response to the varying moisture reminds. Averaged across the moisture regimes, transpiration rate was significantly higher for PE-1 by ~ 46.2, 65.2, 32.4 and 39.2%, respectively over PE-17, C-2045, PE-11 and C-413 clones. There was ~ 58.2% increase in transpiration rate of *Eucalyptus* clones with increase in moisture regimes from CPE_{75} to CPE_{100}. Unsurprisingly, similar to photosynthesis and stomatal conductance rate, the transportation rate decreased significantly by ~ 34.9 and 79.6%, respectively with increase in moisture regime from CPE_{100} to CPE_{125} and CPE_{150}. The relationship between photosynthesis and transpiration rate (Eq. 8) has been illustrated in Fig. 4b. These results revealed that with increase in stomatal conductance, the transpiration rate of different *Eucalyptus* clones exhibited an increase following polynomial function (Eq. 9; Fig. 4c).

$$\begin{aligned}&\text{Transpiration rate}\left(\text{mmol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)\\&=-0.0351\left(\text{Photosynthesis; }\mu\text{mol CO}_2\text{m}^{-1}\ \text{s}^{-1}\right)^2\\&\quad+0.8737\left(\text{Photosynthesis; }\mu\text{mol CO}_2\text{m}^{-1}\ \text{s}^{-1}\right)\\&\quad-0.3559;\ \text{R}^2=0.7143,\end{aligned}\tag{8}$$

$$\begin{aligned}&\text{Transpiration rate}\left(\text{mmol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)\\&=-0.1612\left(\text{Stomatal conductance; mol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)^2\\&\quad+2.1125\left(\text{Stomatal conductance; mol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)\\&\quad-0.7338;\ \text{R}^2=0.7023.\end{aligned}\tag{9}$$

These results revealed that photosynthesis, stomatal conductance and transpiration rates were related to branches + leaves biomass of *Eucalyptus* clones (Fig. 5). These relationships showed that with increase in branches + leave biomass, the rates of photosynthesis, stomatal conductance and transpiration rates were increased. The relationship between these variables could best be described by polynomial equations (Eqs. 10–12).

$$\begin{aligned}&\text{Photosynthesis}\left(\mu\text{mol CO}_2\text{m}^{-1}\ \text{s}^{-1}\right)\\&= -0.008\left(\text{Branches + leaves biomass; kg plant}^{-1}\right)^2\\&\quad + 0.6742\left(\text{Branches + leaves biomass; kg plant}^{-1}\right)\\&\quad - 1.9784;\ \text{R}^2 = 0.5784,\end{aligned} \tag{10}$$

$$\begin{aligned}&\text{Transpiration rate}\left(\text{mmol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)\\&= -0.0011\left(\text{Branches + leaves biomass; kg plant}^{-1}\right)^2\\&\quad + 0.1675\left(\text{Branches + leaves biomass; kg plant}^{-1}\right)\\&\quad + 0.4816;\ \text{R}^2 = 0.5851,\end{aligned} \tag{11}$$

$$\begin{aligned}&\text{Stomatal conductance}\left(\text{mol H}_2\text{O m}^{-2}\ \text{s}^{-1}\right)\\&= -0.0023\left(\text{Branches + leaves biomass; kg plant}^{-1}\right)^2\\&\quad + 0.1901x\left(\text{Branches + leaves biomass; kg plant}^{-1}\right)^2\\&\quad + 0.0143;\ \text{R}^2 = 0.5755.\end{aligned} \tag{12}$$

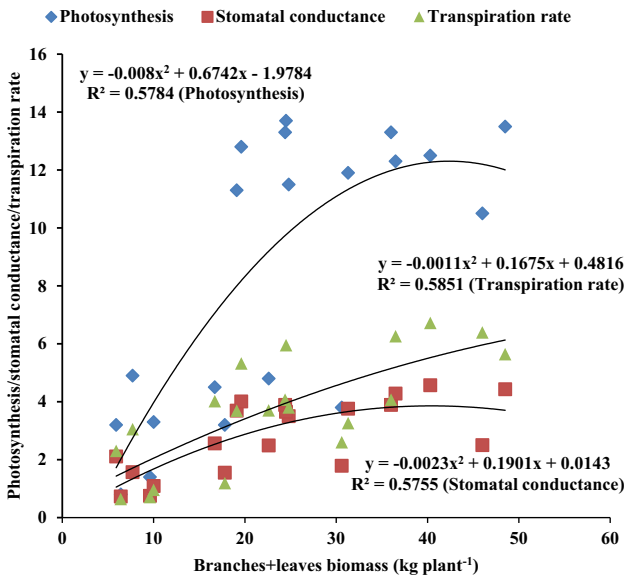

Fig. 5 Relationship between branches + leaves biomass vis-à-vis photosynthesis (μmol CO_2 m^{-1} s^{-1}), stomatal conductance (mol H_2O m^{-2} s^{-1}) and transpiration rate (mmol H_2O m^{-2} s^{-1}) of different *Eucalyptus* clones planted under varying moisture regimes in subtropical north-western India. Data pooled for different clones tested under variable moisture regimes

Correlation matrix and dendrogram depicting relationship between growth attributes

The correlation matrix showed that plant height was linearly related to collar diameter (r = 0.501*; $p < 0.05$), number of branches plant^{-1} (r = 0.549*; $p < 0.05$), number of roots plant^{-1} (r = 0.613**; $p < 0.01$), root length (r = 0.779**; $p < 0.01$), branches + leaves biomass (r = 0.809**; $p < 0.01$) and stems biomass (r = 0.865**; $p < 0.01$) (Table 4). The number of branches showed a linear significant increase with increase in collar diameter (r = 0.868**; $p < 0.01$). Collar diameter significantly increased the branches + leaves biomass (r = 0.833**; $p < 0.01$) (Fig. 6), stems biomass (r = 0.795**; $p < 0.01$) and the roots biomass (r = 0.823**; $p < 0.01$). The increase in branches + leaves biomass was a function of number of branches plant^{-1} (r = 0.806**; $p < 0.01$). The root biomass of *Eucalyptus* clones increased linearly with increased root length (r = 0.627**; $p < 0.01$). The single linkage similarity index depicted through dendrogram showed close association number of branches plant^{-1} and root biomass, as well as between branches + leaves and stems biomass of *Eucalyptus* clones (Fig. 7). The photosynthesis and stomatal conductance was closely linked to transpiration rate, which was plant height and number of branches plant^{-1}.

Discussion

Differential response of Eucalyptus in relation to moisture regimes

The *Eucalyptus* clones respond significantly at variable moisture regimes. The simulation of optimal moisture regime (CPE_{100}) resulted in a significantly higher plant growth as compared to that under either sub-optimal (CPE_{75}) or under super-optimal (CPE_{125}/CPE_{150}) moisture regimes. Similar to these results, Granda et al. (2014) reported considerable variation amongst the nine tested clones of *Eucalyptus globulus* (Labill.) for drought responses. Based upon 31 parameters (physiological, biochemical as well as hormonal), they (Granda et al. 2014) concluded that clones of C-14 group (e.g. C-14, C-120, C-405, C-491 and C-601) behaved as water savers, whilst those belonging to C-46 group (e.g. C-46, C-97, C-222 and C-371) behaved as water spenders and maintained the highest growth rate under moisture stressed conditions.

These results corroborate earlier research findings of Eksteen (2012) who studied the performance of three *Eucalyptus* clones after 18 months of their establishment under three contrasting moisture regimes viz. optimal (no-stress), chronicle stress (mild, long-term and gradual moisture stress) and acute stress (severe stress with periods of recovery from

Table 4 Pearson correlation matrix depicting relation between different growth attributes of *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India

Variables	Tree height	Collar diameter	Number of branches plant^{-1}	Number of roots plant^{-1}	Root length	Branches + leaves biomass	Stems biomass
Collar diameter	0.501*						
Number of branches plant^{-1}	0.549*	0.868**					
Number of roots plant^{-1}	0.613**	0.354	0.382				
Root length	0.779**	0.582**	0.534*	0.617**			
Branches + leaves biomass	0.809**	0.833**	0.806**	0.652**	0.757**		
Stems biomass	0.865**	0.795**	0.786**	0.529*	0.736**	0.954**	
Roots biomass	0.680**	0.823**	0.936**	0.501*	0.627**	0.899**	0.879**

*Correlation significant at $p < 0.05$

**Correlation significant at $p < 0.01$

stress by re-watering) and reported that moisture stress led to a significant reduction in tree volume by up to 10% and leaf area by 30%. While assessing the performance of five commercial hybrids of *Eucalyptus urograndis* established under contrasting moisture regimes simulated at 65, 50, 35 and 20% water retention capacity, Silva et al. (2014) reported that tree height, diameter, number of leaves, leaf area and dry weight of leaf and root: shoot ratio were adversely affected under reduced moisture availability. Soil flooding for initial 40 days induces several morphological changes and resulted in reduced growth of 6 weeks old *Eucalyptus camaldulensis/E. globulus* species (Gomes and Kozlowski 1980). These *eucalyptus* species produced profuse adventitious roots which were originated near tap root and/or the original lateral roots. Continuous flooding reduced the dry shoot weight to a greater extent than the dry root weight in both species (Gomes and Kozlowski 1980; Liu and Dickmann 1992). The increased interval of irrigation scheduling in *Eucalyptus camaldulensis* simulated by moisture deficit conditions resulted in a decreased shoot length and stem diameter of the seedlings with an adverse effect on root and shoot growth (Elobeid 2014). It has been well known that the accumulation of below-ground root biomass has strong relationship with soil moisture availability (Farrell et al. 1996). The highest root biomass accumulation was observed under optimized moisture regimes, while the lowest under conditions where drought like conditions persists. Similar to these results, Silva et al. (2014) observed that tree height, diameter, number of leaves and their dry weight, above-ground (stem and branches) biomass, below-ground (root) biomass, and root: shoot ratio was adversely affected under reduced moisture availability. In a glasshouse study, Davison and Tay (1985) reported that the rate at which wilting appears depend both on the duration of water-logging and the transpiration rate. Both moisture excess and stress results in smaller leaf size and resulted in a significant set-back on leaf expansion (Liu and Dickmann 1992). A 3-weeks continued moisture stress in two genotypes (AL-18 and AL-10) of *Eucalyptus globulus* at 18 and 25% of field capacity resulted in a significant decrease in tree height, above-ground biomass, and water potential and gas exchange (Correia et al. 2014).

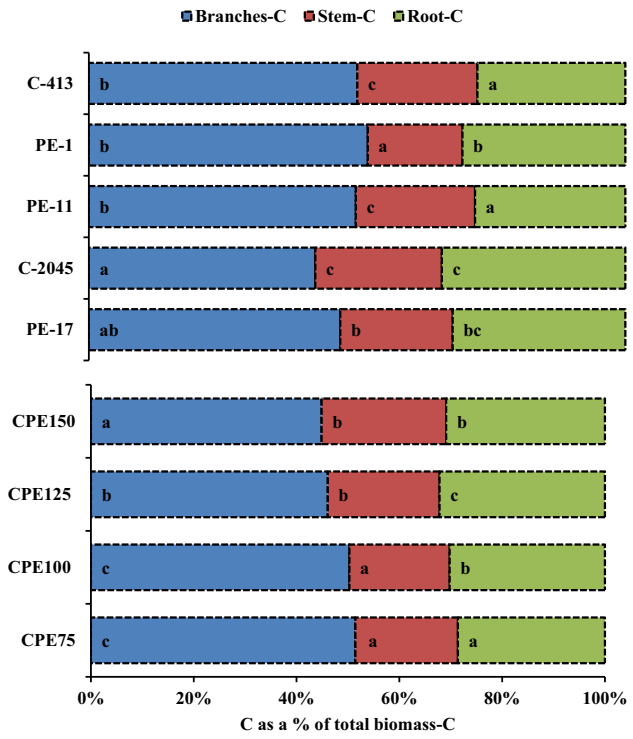

Fig. 6 Carbon storage as a proportion of total biomass-C in branches, stem and root biomass of different *Eucalyptus* clones planted under varying moisture regimes in sub-tropical north-western India. Mean values followed by different letters are significantly different at $p < 0.05$ by least significant difference (LSD) test

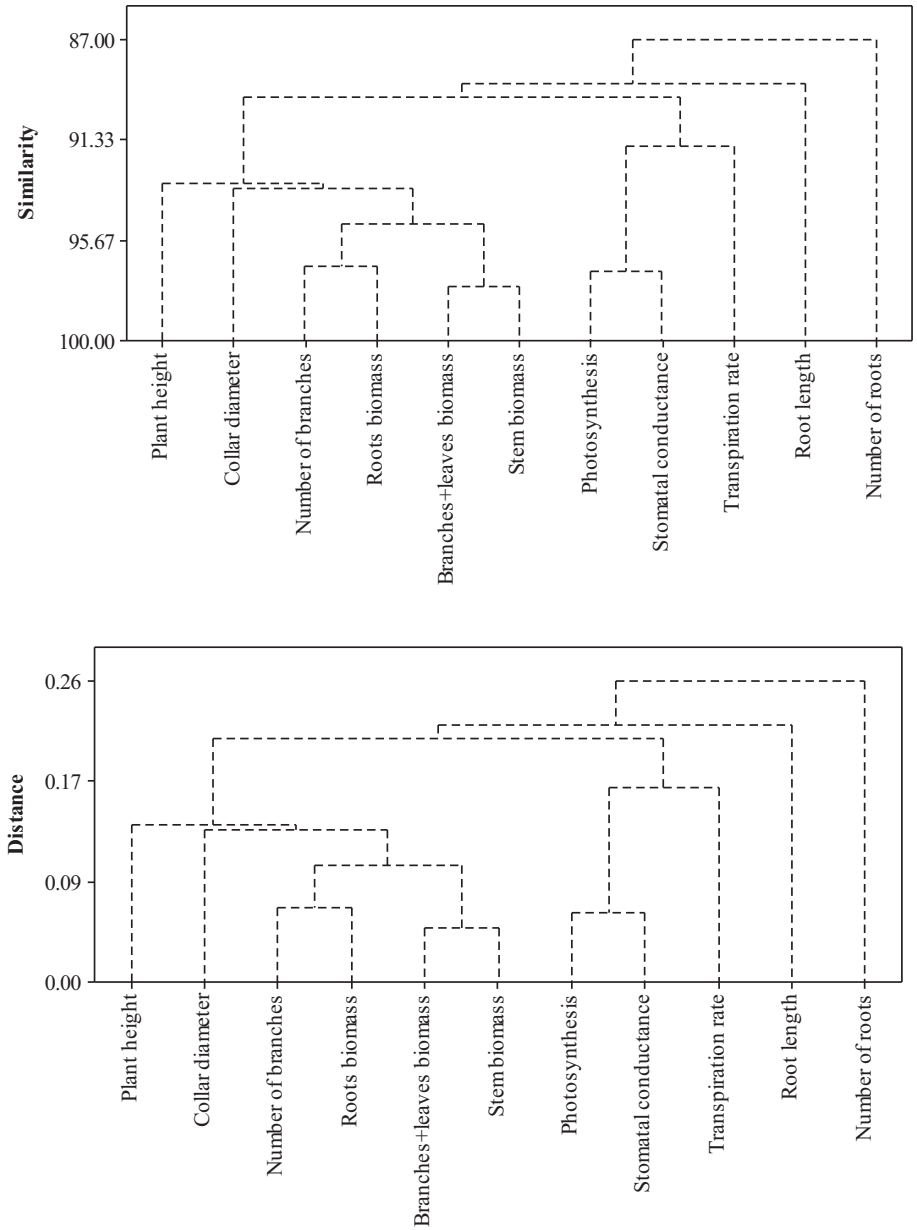

Fig. 7 Dendrogram depicting single linkage similarity and distance between different attributes of *Eucalyptus* clones planted under varying moisture regimes in sub-tropical northwestern India. Data pooled for different clones tested under variable moisture regimes

Moisture regimes vis-à-vis nutrients' transformation

A change in soil moisture regime has significant influence of nutrient availability in soil–plant systems (Singh and Singh 2007, 2010; Singh et al. 2010; Rex et al. 2021). Soil moisture regimes greatly impacts nitrogen (N) transformation and migration, including N-mineralization, nitrification and denitrification processes (Cheng et al. 2014; Rex et al. 2021). The well aerated soils favors the nitrification process and results in enhanced soil nitrate (NO_3^--N) concentration (Girsang et al. 2020), whilst soil submergence resulted in occurrence of denitrification and lead to build-up on ammonical-N (NH_4^+-N) (Singh and Singh 2010; Sun et al. 2020). Conversely, submergence increases the phosphorus (P) availability in soils due to the production of organic acids following decomposition of organic matter under higher moisture regime (Wang et al. 1967), and thereby conversion of meta-stable calcium phosphate to less soluble forms (Singh et al. 2010). But, in the submerged soils the main transformations of sulphur (S) are the reduction of sulphate (SO_4^{2-}) to sulphate (S^{2-}) and the dissimilation of the amino acids, cysteine, cystine and methionine to H_2S (Singh and Singh 2007; Lamers et al. 2012). These changes in moisture regimes significantly influence N uptake and the forms preferred by the plants (Pang et al. 2019; Pokharel and Chang 2021). The decreased soil moisture significantly inhibits plant glycine N absorption by reducing glycine diffusion and relocation from soil to plant roots (Moore and Bubier 2019), and water stress persuaded

by submergence inhibited NO_3^--N uptake rate by decreasing its supply to plant growth (Tang et al. 2020).

Moisture regimes vis-à-vis photosynthesis, stomatal conductance and transpiration

Moisture regimes have variable impact on rate of photosynthesis, stomatal conductance and transpiration by *Eucalyptus* clones. Eksteen (2012) studied the performance of three *Eucalyptus* clones after 18 months of their establishment under three contrasting moisture regimes viz. optimal (no-stress), chronicle stress (mild, long-term and gradual moisture stress) and acute stress (severe stress with periods of recovery from stress by re-watering) and reported that moisture stress led to a significant reduction in tree volume by ~ 10% and leaf area by ~ 30%. Valadares et al. (2014) while comparing five *Eucalyptus grandis* × *E. urophylla* hybrids established under four different moisture regimes under greenhouse structure reported that rate of photosynthetic activity, transpiration, stomatal conductance, leaf water potential, leaf relative water content, photochemical efficiency and chlorophyll content index were highly responsive to moisture stress conditions, and exhibited a considerable decrease under stressed environment. Moisture shortage resulted in a significant decrease in growth and physiological traits e.g. leaf area, above-and below-ground biomass production and physiological characteristics of *Eucalyptus moluccana* clones (viz. CCV-2, and VM-1, a drought tolerant clones) (Silva et al. 2016). The establishment of *Eucalyptus* clones (AR-3, CN-44 and MP-11) under well watered, moderate soil moisture deficit and severe soil water deficit conditions (similar to those maintained in the present study) resulted in a similar effect on transpiration efficiency under moderate and severe moisture stress regimes because of stomatal closure (Osório et al. 1998).

Pita and Pardos (2000) reported that leaf size, specific leaf area, transpiration and tissue water relations in leaves of rooted cuttings of *Eucalyptus globulus* Labill was reduced when trees were established under well-watered or drought conditions. Amongst the clones tested under drought conditions, the highest leaf expansion and the highest increase in transpiration were observed for those which has early and large decrease in Π_0 and Π_{100} (Pita and Pardos 2000). In contrast to these results, Florentine and Fox (2002) reported a significant increase in stem diameter of *Eucalyptus* species established under long-term water-logged conditions, although the rate of photosynthesis, transpiration and stomatal conductance were decreased significantly by flooding. Notwithstanding the effect of continuous flooding on increased diameter of stems, *Eucalyptus* species which are intolerant to excess moisture seldom express morphological adaptations and thereby, disastrous to recover from the physiological damage (Florentine and Fox 2002). The loss of water in excess to that compensated from soil caused a significant reduction in leaf area ratio, specific leaf area and leaf-to-root area ratio (Silva et al. 2004).

A greater decrease in roots as compared to the leaves of *Eucalyptus* was ascribed to the increased concentrations of soluble sugars and proline in these organs, while the activity of glutathione reductase enzyme increased significantly in response to water deficit (Shvaleva et al. 2005). Under root hypoxic conditions, the seedlings of *M. cajuputi* are reported to maintain high growth while the *E. camaldulensis* showed decrease in growth compared to control seedlings. Root hypoxia led to decrease in stomatal conductance and photoassimilate transport to roots in *E. camaldulensis. M. cajuputi* showed sustained photoassimilate transport (Kogawara et al. 2006). The net photosynthetic rate, stomatal conductance and transpiration rate rapidly reduced for C-2 and C-4 clones of *Eucalyptus camaldulensis* (Dehn.) after 16 days of water-logging than the C-1 and C-3 clones (Youngsukying and Nakasathien 2008). Earlier research highlighted that defoliation of *E. globulus* resulted in a transient increase in foliar photosynthesis (Pinkard et al. 2007). Nonetheless, the increased assimilation in the remaining leaf tissue could at least partially been compensate by the loss of photo-synthetically active tissue and lost assimilates (Quentin et al. 2010). The reduction in moisture availability resulted in a decreased biomass production with a greater influence on roots than shoots, such that low watering supply reduced root: shoot ratios (Manoharan 2002). The *Eucalyptus* species of high rainfall environments (*E. obliqua*, *E. rubida*) and the phreatophyte (*E. camaldulensis*) had lower osmotic potential under moisture deficit regimes due to osmotic adjustments, whereas the species belonging to low rainfall environments (*E. cladocalyx*, *E. polyanthemos* and *E. tricarpa*) had lower osmotic potential through a combination of both constitutive solutes and osmotic adjustment, combined with reductions in leaf water content (Merchant et al. 2007). In general, *Eucalyptus* plants under moisture stressed environment respond by decreased rate of transpiration via controlling stomatal conductance and by provoking C shortage for photosynthesis and decreased net CO_2 assimilation (Whitehead and Beadle 2004; Graciano et al. 2005; Warren et al. 2011; Utkhao and Yingjajaval 2015). However, under extreme and prolonged moisture stress, *Eucalyptus* trees shed their leaves to reduce the net transportation rate (Snowdon 2000; Warren et al. 2011; Nouvellon et al. 2010). Another adaption strategy of increased allocation of assimilated food in the root biomass of *Eucalyptus* under moderate moisture stress conditions to maximize water uptake was not observed in the present study (Snowdon 2000; Whitehead and Beadle 2004). Even at a cellular level, *eucalypts* species are known to maintain cell turgor under moisture deficit environments, which are created by the active accumulation of organic solutes e.g.

proline and/or by adjusting the elasticity of cell walls (Graciano et al. 2005; Warren et al. 2011, 2012).

Moisture regimes vis-à-vis plant growth attributes

While the *Eucalyptus* species are highly productive across the globe, their above-and below-ground C sequestration potential is highly site-specific; depending upon the management differences, different genotypes respond differentially under cultural intensity, planting density, and rotation length (Zhou et al. 2016; Rockwood et al. 2022; Avtar-Singh et al. 2022). The moisture regimes at which *Eucalyptus* clones are established greatly impacts tree growth attributes and eventual C flow in different components (Avtar-Singh et al. 2022). The finer root (< 2.0 mm) biomass has greater role in ecosystem restoration due to C storage (Du et al. 2015). Although, root biomass has been the smallest fraction in forest ecosystems, yet fine-root growth comprised ~ 1/3rd annual net primary production, highlighting considerable potential of roots in allocation of net C assimilated (Chen et al. 2013; Rieger et al. 2013; Varik et al. 2013). The importance of root biomass could be ascertain from the fact that these components of net primary production are more effective pathways for accrual of soil organic C stocks, compared with the above-ground biomass components (Rasse et al. 2005; Gonzalez et al. 2013). Although, C sequestration in tree components has been the function of stand age, the stem biomass has the highest proportion of biomass C sequestered (Claus and George 2005; Bojra et al. 2008; Du et al. 2015). The stomatal closure under prolonged moisture stressed environments damage the chlorophyll and photosystems by decreasing the photosynthetic capacity. The resultant decreased photosynthetic activity caused the reduced assimilation of C in different above-and below-ground biomass components of *Eucalyptus* clones.

Conclusion

These results revealed significant differences in growth attributes and rates of photosynthesis, transpiration and stomatal conductance by different *Eucalyptus* clones under contrasting moisture regimes. The plants established under optimal (CPE_{100}) moisture regimes had significantly higher growth e.g. plant height, collar diameter and number of branches plant^{-1} increased by 8.9, 9.3 and 63.6%, respectively than those established under sub-optima (CPE_{75}) moisture regime. Plant establishment under super-optimal ($CPE_{125–150}$) moisture regimes significantly decreased the growth attributes as well as the rates of photosynthetic activity and stomatal conductance. The fresh and dry biomass of different components of net primary production was significantly higher under CPE_{100}, while decreased under both sub-optimal and/or super-optimal moisture regimes. Amongst the different clones tested, PE-1 has significantly higher collar diameter, number of branches/roots plant^{-1}, and dry branches + leaves and roots biomass, compared with other clones. The PE-1 clone has significantly higher total biomass-C (by ~ 40 to 154%), compared with the others. These results highlight that the tested *Eucalyptus* clones has high potential for increased net primary productivity when established under CPE_{100}.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article.

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