INFLUENCE OF PLANTING DENSITY AND PRUNING ON THERMAL, RADIATIVE AND MOISTURE REGIMES IN *Acacia mangium* Willd. STAND

By

HARSHA C

(2013- 17- 110)

THESIS

Submitted in partial fulfillment of the requirement for the degree of

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DECLARATION

I hereby declare that the thesis entitled "**INFLUENCE OF PLANTING DENSITY AND PRUNING ON THERMAL, RADIATIVE, MOISTURE REGIMES IN *Acacia mangium* Willd. STAND**" is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title of any other University or Society.

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CERTIFICATE

Certified that thesis entitled "**INFLUENCE OF PLANTING DENSITY AND PRUNING ON THERMAL, RADIATIVE, MOISTURE REGIMES IN *Acacia mangium* Willd. STAND"** is a record of research work done independently by Mr. Harsha. C under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship to him.

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Introduction

1. INTRODUCTION

Acacia mangium is a fast-growing tree, which is native to Northern-Australia and well-known nitrogen-fixing tree, being used for land rehabilitation, particularly in eroded and nitrogen-deficient soils (Doran and Turnbull, 1997). It is one of the many exotic trees that have been introduced into India in the past. In Kerala, *Acacia mangium* has become one of the favoured species for cultivation by farmers who prefer this tree as a component in their landholdings because of their vigorous growth rate, absence of major disease and wide range of uses including fuelwood and timber. This tree is mainly preferred in industrial wastelands and nutrient poor soils because of their tolerance to highly acidic and low nutrient soils (National Research Council, 1983).

The microclimate encompasses the suite of climatic conditions that exist in a localized area near the earth surface (Chen *et al.*, 1999). The variables that define the microclimate (e.g., temperature, solar radiation, wind speed and direction, and moisture) influence ecological processes such as the establishment, growth and development of plants (Geiger *et al.,* 2003). Vegetation density, structure, canopy closure and other management practices also influence the microclimate. It is well known that planting density and pruning at a stand level can alter the crown architecture and stand structure that in turn determines plant growth and development, soil nutrient cycling, organic matter decomposition and primary productivity (Chen *et al.,* 1993). This can change microclimatic variables such as light penetration, temperature, vapour pressure deficit and wind speed (Landsberg and Sands, 2011) and water supply from the soil (Bréda *et al.*, 1995). This, in turn, can bring substantial changes in the stand productivity and can also alter the resource acquisition potential of individual tree. Therefore, adequate knowledge about planting density and pruning levels are essential for the effective utilization of available resources and also in the development of plantation technology.

Planting density plays an important role in the modification of microclimate parameters such as air temperature, soil temperature, relative humidity and radiation (Dela Cruz and Luna, 1994). As tree density in a plantation decreases, mutual interference between trees both above and below the soil surface will decrease and the magnitude of the microclimate parameters will be modified. More specifically, there is likely to be less competition for resources by roots between trees, reduced mutual shading and increased canopy boundary layer conductance (Medhurst *et al.*, 2002). On the other hand, increase in planting density may also increase the efficiency with which trees and stands use water. Higher resource acquisition or availabilities have been associated with higher water use efficiency of trees and stands (Stape *et al.*, 2004). Planting density effects on water use efficiency have received little attention, but this information provides an important basis for linking silvicultural interventions in managing water resources (White *et al.*, 2009).

Silvicultural interventions like pruning is commonly applied to forests and plantations to increase growth rates and improve the wood quality of retained trees (Forrester *et al.*, 2010). The removal of part of the trees leaf area as well as reducing the ratio of leaf area to sapwood area by pruning leads to reduction in transpiration. These changes may affect soil moisture availability and the water status of the retained leaves as indicated by increases in stomatal conductance and photosynthetic rates that often follow defoliation (Pinkard and Beadle, 1998). These leaf-level compensatory responses to pruning or defoliation are often transitory, disappearing as the leaf area is rebuilt (Pinkard *et al.*, 2004; Quentin *et al.*, 2011). Trees can acclimate to these changes and maintain a homeostatic balance between stomatal conductance, the soil to leaf water pressure gradient (DW), and hydraulic architecture parameters (Whitehead *et al.*, 1984). However, the influence of pruning on stand microclimate and WUE has received little attention.

Both of these interventions have complex effect on biomass production, microclimate and water use efficiency through the change of energy fluxes and water balance across the plantation. Therefore, the modification of microclimatic conditions and achieving higher water use efficiency by standardisation of spacing and pruning levels offers a good scope for the development of plantation technology for *Acacia mangium* and thereby offers additional returns to the farmers.

The present study was formulated in this backdrop to give information on eco-physiological properties of *Acacia mangium* plantation with the following objectives.

1. Study of thermal, radiative and moisture regimes under different planting densities and pruning regimes in *Acacia mangium* stand.
2. Estimation of water use efficiency of *Acacia mangium* as influenced by plant density and pruning.

Review of literature

2. REVIEW OF LITERATURE

Plantation forestry not only offers opportunities for meeting wood demands and reducing deforestation by decreasing pressure on natural forests but also restores degraded soil and enhance biodiversity (Parrotta, 1992). An attempt has been made in ensuring sections to critically review the literature on the role of planting density and pruning on modifying microclimatic conditions such as temperature, relative humidity, soil moisture, photosynthetically active radiation (PAR) and evapotranspiration. Water use efficiency associated with planting density and pruning are also reviewed hereunder.

2.1. MICROCLIMATIC FACTORS

Forest plantations have a distinct below-canopy microclimate, regulated by diverse biophysical processes. This has importance to the growth and survival of understorey vegetation and seedlings. Canopy and tree stems partly shield near ground areas from solar radiation and reduce mixing of air. As a consequence, below-canopy microclimate may substantially differ from the open areas (Geiger *et al.,* 2003). Inside the tree stands, air temperature (T) usually decreases less during the night and increases less during the day, whereas the tightly coupled relative humidity (RH) shows the opposite pattern (Morecraft *et al.,* 1998; Aussenac, 2000; Ma *et al.,* 2010; Von arx *et al.,* 2012). This smoothing effect on the daily T and RH amplitude is not uniform, but depends on the ambient weather situation and season (Renaud *et al.,* 2011; Von arx *et al.,* 2012; Morecraft *et al.,* 1998), structure and physiographic situation such as elevation, slope and aspect (Mitscherlich, 1981; Von arx *et al.,* 2012). While shading by the canopy affects both soil and air temperature, the direct effect on air temperature is assumed to be smaller (Morecraft *et al.,* 1998 and Porte *et al.,* 2004), mainly because air is mobile, as well as partly mixed and exchanged with the open area. Consequently, vegetated soils generally warm up less than the open area leading to a diminished sensible heat flux (Mitscherlich, 1981).

Furthermore, the colder below-canopy temperature results in a higher relative humidity inside the stand, when assuming constant absolute air water content. An additional impact of soil on microclimate results from evaporative cooling or latent heat flux. Moist soils thus attenuate warming up of the air and lowering of relative humidity (Seneviratne *et al.,* 2006; Ferranti and Viterbo, 2006; Fischer *et al.,* 2007; Hirschi *et al.,* 2011; Jaeger and Seneviratne, 2011). While basic principles of stand microclimate and the relationships with open-area microclimate, therefore, seem established, a more functional and quantitative view on how the properties of tree stands influence below-canopy microclimate is largely missing (Breshears *et al.,* 1997; Chen *et al.,* 1999; Scharenbroch and Bockheim, 2007; Vanwalleghem and Meentemeyer, 2009).

For survival and growth of young tree seedlings, for instance, favourable temperature, air humidity and soil moisture are crucial determinants, especially until the root system is sufficiently developed and other factors such as light conditions and nutrient availability become limiting (Aussenac, 2000). In fact, at the initial life stage, many seedlings die within hours if conditions are unfavourable (Harper and White, 1974). Temperature affect the growth rate metabolism and influences the plant water demand. Similarly, the soil temperature has been shown to influence root water uptake and thus transpiration rates (Mellander *et al.,* 2004). To reduce the short-term water demand, stomata often close when soil moisture or air humidity are low (Ladjal *et al.,* 2007; Aasamaa and Sober, 2011). Effectively, stomatal conductance is usually regulated by a simple negative feedback loop between vapour pressure deficit of the air (VPD) and soil moisture (MaierMaercker, 1998). The balance of this feedback loop varies among species depending on their specific ecophysiological requirements and strategies

Yet, some studies reported that closed stomata in herbaceous plants and tree seedlings even when there was ample soil moisture if the air was considerably dry and vapour pressure deficit elevated (Leuschner, 2002; Lendzion and Leuschner, 2008; Kupper *et al.*, 2011). Stomatal control and photosynthetic efficiency are also influenced by levels of CO_2 in the air (Kramer and Boyer, 1995), which is additionally released from the forest floor by decomposition processes and root respiration particularly when soils are moist and warm (Deng *et al.*, 2010; Lloyd and Taylor 1994; Raich and Tufekciogul, 2000).

The interplay of all above-mentioned microclimatic and microsite factors changes during the growing season and so does the impact of these factors on plant processes (Wu *et al.*, 2012; Ogle *et al.*, 2012). So it seems important to improve our understanding of how microclimate is influenced by the key determinants such as air temperature, vapour pressure deficit and soil moisture.

2.2. THERMAL ENVIRONMENT

Temperature is a crucial factor involved in determining the rates of biochemical reactions and it has a strong influence on plant and root growth (Jimenez *et al.*, 2007; Facelli and Pickett, 1991). Cambial activity, cell differentiation and many other physiological parameters are affected by temperature (Oribe *et al.*, 2001; Begum *et al.*, 2007; Rossi *et al.*, 2008). Diurnal soil temperature range is particularly important in plant growth, such as seed germination and early seasonal growth which are highly correlated with daily maximum temperature of the soil rather than with air temperature (Song *et al.*, 2013).

2.2.1. Planting density and temperature

Several studies have looked at the effects of stand densities on surface microclimate parameters up to two meter height. Anderson *et al.* (2007) found that mean air temperature maximum was 1- 4° C higher in the thinned stand than the unthinned stand.

Groot and Carlson (1996) found that air temperature decreased as forest opening increased, with an average difference of nearly 3° C between the clear-cut and forest area. In western Washington, Heithecker and Halpern (2006) observed increase in mean and maximum air temperatures with decrease in the amount of live tree retention. However, none of these studies examined temperature or humidity gradients through the vertical forest profile. Therefore, number of studies which examine the microclimatic variation along the vertical profile are limited.

Forest trees modify their canopy microclimate like temperature along a vertical gradient. Air temperature generally declines with canopy depth due to within crown shading. Zweifel *et al.* (2002) observed about a 1° C temperature change approximately every 4 m from the upper to lower canopy over 22 m in a *Picea abies* forest. A study of microclimate conditions at three heights in Douglas-fir canopies (1, 3, 5 m), observed that mean temperature at one metre height in the low density planting was 67 % of that in the high density but temperature did not vary significantly between the planting densities at three and five metre heights (Woodruff *et al.,* 2002).

A study on the effects of planting density and stand management on upland pasture production to evaluate the microclimate under various tree canopy structures revealed that temperature was greater at the wider spacing as compared to closer spacing (Sibbald *et al.,* 1992). Temperature inside the plantation of *Acacia mangium* decreased vertically with height, above the ground level.

The changes in the temperature at different height (0.5, 2, 7 and 16 m above the ground level) were more distinctive in the dry season than in the wet season (Sinoquet and Bonhomme, 1995), while another study in a *Robinia pseudoacacia* plantation, the air temperature didn't show any significant changes at different heights above the ground surface (Zhang *et al.*, 2013).

2.2.2. Pruning and temperature

The removal of branches by pruning allows more turbulent mixing of air, which in turn allows the more PAR to reach the ground surface. This results in greater temperature under the pruned stands. In a study of *Albizia procera*-based agroforestry system in Jhansi, it was found that temperature was significantly higher under the canopies of pruned trees than the unpruned trees while in the open area, temperature was 9 % higher than the agroforestry system (Newaj *et al.*, 2007). A study on the effect of pruning intensity in the mango orchard revealed that severe pruning led to the better PAR penetration and increased the canopy temperature, but PAR was declined with the reduction intensity of pruning (Singh, 2009). Similarly, observations in 14 year old mango orchard revealed that canopy temperature was highest under severe pruning and lowest under light pruning (Pratap *et al.*, 2003). In a coffee plantation, it was observed that the temperature which was measured at different heights before pruning was similar, but after pruning, the maximum daily temperature near the surface was higher than above the canopy (Saini *et al.*, 1997). Therefore, they concluded that after the pruning there is a tendency to increase the thermal amplitude inside the canopy.

2.2.3. Soil temperature

Many sources indicated that soil temperature is lower under the tree canopies due to shading. For example, in semi-arid Kenya, soil temperatures at 5 cm depth was lower than the grassland by 4° C, both at the beginning of the growing season and when the grass cover was at a maximum (Belsky *et al.*, 1989). The difference between the locations decreased with soil depth.

Similarly, a study in seven year old *Acacia mangium* plantation revealed that mean soil temperature at 0-20 cm depth under the plantation was lower than the open condition by 2° C and the effect was more obvious in the dry season (Sinoquet and Bonhomme, 1995). Soil temperature was substantially lower under the Vitellaria and Parkia trees than in the open (Johnson, 1995).

2.2.3.1. Planting density and soil temperature

Experiments have shown that soil temperature increased as density decreased (Facelli and Pickett, 1991; Scull, 2007). Solar radiation is intercepted or reflected by plants reduce the absorption of radiation by soil and resulted in lower soil temperature. Reduced planting density decreased the difference between air and soil temperatures in the growing season. This is caused by the reduction of vegetation height and density and increasing the heat flux between soil and atmosphere. The variation of the difference between air and soil temperature may alter the microenvironment and affect the structure and dynamics of the plantation. For example, the growth rate of plants at both aboveground and belowground would respond to the variation of temperature (Green, 1984), which in turn would influence the interactions and feedbacks between plant and soil. Zheng, (2011) found that decreasing the temperature difference between soil and air temperature significantly affected the root length and its distribution.

2.2.3.2. Pruning and soil temperature

Generally, pruning increases soil temperature due to the opening of canopy that led to the better penetration of PAR into the soil surface. A study by Shangwei *et al.* (2009) in a poplar based agroforestry system observed that soil temperature was maximum under the pruned stands as compared to the unpruned stands due to opening of the canopy. Similarly, another study in an *Albizia procera* based agroforestry system also reported that soil temperature was significantly higher under the canopies of pruned trees than the unpruned trees (Newaj *et al.*, 2007).

2.3. MOISTURE ENVIRONMENT

To get clear picture of the water balance of a locality, it is important to quantify the parameters such as rainfall, evapotranspiration, soil moisture and water status of trees. These parameters are essential for many applications like irrigation scheduling, plant stress monitoring and improving the yield of a plantation. It also determines the partitioning of net radiation into latent and sensible heat components in the field of meteorology. Thus, these information play an important role in the water and energy budgets necessary for microclimate studies.

2.3.1. Planting density and soil moisture

Many studies indicated that the soil moisture content was inversely related to planting density. Although higher planting density reduces radiation at the soil surface, it increases the radiant energy absorbed by trees leading to accelerated soil moisture depletion through transpiration (Rey, 1999). It was observed that the soil moisture was depleted much more actively where stand is denser as compared to that of the sparse stand in a red pine stand (Chris, 2001). Similar results also observed for 15 year black locust plantation (Wang *et al.,* 2002), shade trees in tea garden (Pereira, 1959), *Fagus sylvatica* plantation (Stiptsov, 1995), Scot pine (*Pinus sylvestris*) plantation (Rodriguez-Calcerrada *et al.,* 2008) and 7 year old *Acacia mangium* plantation (Skaraiah, 2008). Opposite trends have been reported for the 17 year old *Ailanthus triphysa* plantation (Rakesh, 2009).

Contrary to all this, there are reports of soil moisture not being affected by planting densities. A study in an *Acacia saligna* agroforestry planted at density of 2520, 1330, 840 trees/ha, indicated that tree planting density did not affect the soil moisture content and productivity (Sauerhaft, *et al.,* 1999).

2.3.2. Pruning and soil moisture

Tree pruning decreased soil moisture depletion compared with the non-pruned trees due to the removal of lower and least efficient foliage (Dropplermann *et al.,* 2000). A study on the effect of pruning on soil moisture and growth of apple trees revealed that soil moisture in 0-240 cm depth was significantly increased by pruning, but it had no significant effect below a depth of 240 cm (Li *et al.,* 2012). Similarly in a poplar based agroforestry system, soil moisture content was significantly higher under the pruned trees at 20-80 cm depth. However, it did not vary significantly from the open site at 0-20 cm depth (Douglas *et al.,* 2006). Opposite to this, soil moisture content of shallow depth was reduced by pruning and this have been reported for the citrus orchard (Souza *et al.,* 2004) and a poplar based agroforestry system (Shangwei *et al.,* 2009) due to the exposed surface layer.

Contrast to all the above studies, a study by Jackson *et al.* (2000) reported that pruning of the tree canopy did little to limit the water demand of tree component, leads to no changes in the soil moisture content.

2.3.2.1. *Seasonal and profile variation of soil moisture*

The higher soil moisture content under the woody canopies than in the treeless sites appears to be a common pattern during the rainy season and some time afterwards. This may be due to the rapid evaporation of soil moisture from the surface layer and also, the soil supports water movement to the deeper layers. For instance, soil moisture at 0–10 cm depth during the end of the rainy season was twice as high under *F. albida* canopies as in the open probably due to the lower evapotranspiration rate (Charreau and Vidal, 1965). A similar pattern was also observed for the pruned *Faidherbia* trees in the early and late season (Depommier, 1996). Dancette and Poulain (1969) was also found that soil moisture was higher under the *F. albida* trees than in the open at 120 cm depth, but it was lower in the deeper horizons (down to 4 m) due to water absorption by deep tree roots. During the rainy season, water reaches deeper horizons under the trees than in the open because of the better infiltration and reduced evapotranspiration.

A study by Jirasuktaveekul *et al.* (1992) found that soil moisture content was 30-35 % lower in a three year old eucalyptus plantation at different depths as compared to that of abandoned areas. Similarly in Thailand, the soil moisture content in first meter of soil under a three year old eucalyptus plantation was found to be almost half than in the surrounding abandoned land. Studies undertaken by Cinnirella *et al.* (1993) reported that stand thinning resulted in greater soil moisture content in the Douglas fir plantation. However, Studies by Ngebgba *et al.* (2001) revealed that soil moisture content was not significantly different between the plantation and natural vegetation.

Soil moisture in the unspecified soil depth and period was significantly lower (4.7 versus 9.3 percent) in the open than under both *Hyphaene thebaica* and *F. albida* in Kareygorou (Moussa, 1997). Decrease in the top soil moisture with increasing distance from *V. paradoxa* trees was reported towards the later part of the rainy season in southern Burkina Faso (Boffa *et al.*, 1999). In Malawi, soil moisture was not higher under small *F. albida* trees than in the open, as their leafless canopies did not create enough shade to reduce evapotranspiration. However, surface soil moisture was consistently higher under the large crowns throughout the growing season (Rhoades, 1995). Similar findings result from comparing trees with different crown sizes due to pruning. For example, Zoungrana *et al.* (1993) measured a more rapid decrease (5 versus 8.6 percent) and lower content of soil moisture (10 versus 12 percent) under the *Azadirachta indica* trees (crown radius 3 m) pruned two years earlier than under the unpruned ones (radius ≥ 3 m). It should also be noted that differing tree shape affects the way species influence microclimate and soil water. In northern Senegal, higher evapotranspiration in the *Acacia tortilis* than *B. aegyptiaca* stands was attributed either to the higher interception of the former's spreading crown or to its higher absorption/transpiration (Nizinski and Grouzis, 1991).

In contrast to the above studies, larger canopies may also reduce soil moisture by generating more evapotranspiration due to their more extensive exchange surface between foliage and air. This is especially true towards the late part of the rainy season when rainfall events become less intense and frequent and temperature rises. For example, Diakite (1995) reported that soil moisture under small *V. paradoxa* canopies (9.9 m diameter) was significantly higher than under larger crowns (15.4 m diameter) in September (0.144 versus 0.131 g water/g of dry soil) and October (0.0824 versus 0.0644 g).

2.3.3. Planting density and evapotranspiration

Trees influence the evapotranspiration through effects on microclimate and soil water content (Ong and Monteith, 2007; Liu *et al.*, 2008). The microclimatic factors most likely to be modified are solar radiation receipts at ground level and wind speed (Wallace, 1996). However, aerodynamic factors such as wind speed are less important in the relatively closed canopies provided by well-established tree fallows and rotational woodlots. Hence, solar radiation is the major factor that influences the evapotranspiration (Yang *et al.,* 1990; Zhang *et al.,* 2010). Evapotranspiration is also influenced by the soil nutrients and moisture conditions (Sosebee and Weibe, 1971; Ovaska *et al.,* 1992; McJannet *et al.,* 2001; Zeppel *et al.,* 2004), humidity of air adjacent to leaves (Whitehead *et al.,* 1984; Jarvis and McNaughton, 1986) and the supply of water from conducting stem tissue (Wulleschelgar *et al.,* 1998). Evapotranspiration can also be affected by the planting density (Allen *et al.,* 1998). The transpiration rate of plants increases at the closest spacing due to the well-exposed leaf area at the top of the plants (Papadopoulos and Ormond, 1988).

A study in a *Eucalyptus grandis* plantation, which was planted at 3 spacing's (82, 304, and 2150 stems/ha) revealed that water loss per unit area by evapotranspiration increased with an increase in the planting density and at the closer spacing, subsoil water contents were depleted up to wilting point (Eastham *et al.*,1990). Guttormsen (1974) also reported that greater planting density can result in a higher total evapotranspiration. If there is plenty of water in the soil, the evapotranspiration depends on the radiation reaching the ground or surface of the vegetation. The higher interception by spreading crown or to its higher absorption/transpiration leads to higher evapotranspiration in the high density planting, even though it reduces the radiation that reaches the soil surface (Nizinski and Grouzis, 1991).

However, few studies reported that evapotranspiration rate was increased with an increase in stand density. Eastham and Rose (1988) found that evapotranspiration in the *Eucalyptus grandis* plantation was lower at the closer tree spacing compared to the wider spacing due to the reduced radiation and stomatal conductance. Similarly, a study conducted in a silvopastoral agroforestry system found that transpiration rates per tree were lowest at the high density stand being 12.9 x 10^{-3} m^3 /day compared with the low density stand (72.9 x 10^{-3} m^3 /day) (Eastham *et al.*, 1990). However, water use efficiency was found to be highest in the densely planted trees. In tulip trees, evapotranspiration per plant decreased with an increase in plant density (Vandervelk, 1999).

Contrast to all the above studies, the evapotranspiration was not affected by pruning have been reported for the birch seedlings which are grown under the elevated CO_2 at different planting densities (Zhang *et al.*, 2008) and 12 year old *Pinus radiata* stand (Huber and Trecaman, 2002).

2.3.4. Pruning and evapotranspiration

Pruning of the live branches is a management option to enhance wood quality in plantation trees. It may also alter the whole-tree water use, but little is known about the extent and duration of changes in transpiration. A good understanding of the magnitude and duration of pruning effects on the transpiration may enable the pruning to be used as a buffer against the drought-related stress (Alcorn *et al.*, 2012).

The removal of leaves reduces the amount of light intercepted and rates of evapotranspiration. This reduction in resource use can reduce evapotranspiration although growth is often unaffected by pruning in vigorous unthinned stands as long as no more than about 40–50% of the length of the live crown is removed in a single pruning lift (Bredenkamp *et al.*, 1980; Pinkard and Beadle, 1998; Pinkard *et al.*, 2004; Forrester *et al.*, 2010). For instance, the growth of *Pinus* species decline only after about 20–30% of the live crown length has been removed (Luckhoff, 1949 and Karani, 1978). Rapid reductions in the photosynthetic leaf area following shading, disease or defoliation have the potential to dramatically alter the evapotranspiration, although not necessarily in proportion to the leaf area reduction (Pepin *et al.*, 2002 and Whitehead *et al.*, 1996). For instance, the removal of about 45% (Quentin *et al.*, 2011) or 60% (Quentin *et al.*, 2012) of the leaf area of *Eucalyptus globulus* tree crowns resulted in higher transpiration per unit leaf area while pruning 75% of the leaf area of the *Eucalyptus nitens* (200 trees ha^{-1} trees) reduced transpiration by about 16% but it increased the transpiration per unit leaf area, after 2–3 years of pruning. Growth of both eucalyptus plantations were unaffected by pruning. Pruning increased the rates of stomatal conductance in the *Eucalyptus globulus* or *Eucalyptus nitens* (Forrester *et al.*, 2012; Pinkard, 2003). The duration of reductions in evapotranspiration is likely to depend on the species, the intensity of pruning and the climatic conditions followed by pruning. In agricultural systems in semi-arid tropics, tree pruning reduced the evapotranspiration by absolute values of 9 % compared to the unpruned plots (Kinama *et al.*, 2005).

Pruning 50 % of the live crown length of the four year old *Eucalyptus cloeziana* and *Eucalyptus pilularis* trees reduced the evapotranspiration by 59 % for *E. cloeziana* and 39% for *E. pilularis* during the first eight days after pruning compared with the unpruned trees of the same size class (dominant and co-dominant trees) but after 36 days of pruning, there were no longer any pruning effects on the evapotranspiration (Alcorn *et al.,* 2012). In contrast, evapotranspiration was still 16% lower for the pruned *E. nitens* trees, 2–3 years after pruning 50% of the live crown length (75% of leaf area) (Forrester *et al.,* 2012).

2.3.5. Planting density and relative humidity

Plant density is one of the determinant factors of canopy boundary layer conductance (Monteith and Unsworth, 1990; Landsberg and Gower, 1997). Canopy boundary layer reduced the atmospheric mixing, resulting in different concentrations of gases within the canopy compared with that above the canopy (Brooks *et al.,* 1997). Calm wind conditions at night results higher carbon dioxide concentrations within a forest in response to soil and plant respiration, the lack of photosynthesis, and low atmospheric mixing (Buchmann *et al.,* 1996; Brooks *et al.,* 1997; Anthoni *et al.,* 1999). This condition may result in substantially higher CO_2 levels around plant foliage in short canopies with low canopy roughness and low coupling with the atmosphere. A low boundary layer conductance could result in the maintenance of elevated CO_2 concentrations in the morning hours before atmospheric mixing increases with an increasing radiation and wind speed. This would increase morning photosynthetic rates. A low canopy boundary layer conductance increase humidity levels within a stand in response to the trapping of water vapour from plant transpiration and soil evaporation. Stomata may respond to increased humidity by opening more or remaining open longer throughout the day, resulting in increased photosynthesis as well as increased photosynthetic water use efficiency (Hall and Scurlock, 1993; Harrington *et al.,* 1994; Waring and Winner, 1996).

Hence, the increased stocking density may enhance humidity within a stand at least until shading becomes limiting, resulting in greater growth at the individual tree level. A study in a *Leucaena leucocephala* alley cropping system, results revealed that relative humidity and leaf wetness duration decreased with an increase in alley width (Koech and Whitebread, 2000). In contrast, a study in a fifteen year old red pine stand revealed that the variation of humidity in both the dense canopy and open canopy have little difference (Caramori *et al.,* 1996).

2.3.6. Pruning and relative humidity

A study conducted to observe the effect of pruning intensity on microclimate modification in mango trees under the high density planting revealed that the relative humidity was highest (61.4%) in the unpruned trees and lowest in the severely pruned trees (53.4%) (Sharma and Roomsingh, 2006). Similarly, another study in a mango orchard found that relative humidity which was highest under control (no pruning), decreased with increase in the intensity of pruning (Pratap *et al.,* 2003). Similarly, pruning decreased the relative humidity to 13% as that of pruned plots in a poplar based agroforestry system (Shangwei *et al.,* 2009). A study of microclimatic changes in an *Albizzia procera* agroforestry system revealed that humidity and shade length was higher under the unpruned trees as compared to the pruned trees, humidity which was 25% higher in the agroforestry system as compared to the open field (Newaj *et al.,* 2007). In a coffee plantation, the relative humidity was decreased 10 % by pruning treatments (Rolim *et al.,* 2008). Reduction of relative humidity inside the canopy was pronounced mainly between 8.00 h and 15.00 h. This indicated that pruning caused a reduction in relative humidity during the day inside the plantation.

2.3.7. Relative Water Content (RWC)

Olive trees grown at different planting densities showed the maximum values for leaf water potential in spring and the minimum values in summer (Guerfel *et al.,* 2010). It was observed that the highest planting density was associated with lower water potential in month of August. However, in September, the water potential and relative water content of all planting densities were almost similar due to the rainfall and lower temperature. Similarly, in a *Fagus sylvatica* plantation, the moisture content of trees tended to decrease with the decreasing plant density and productivity was greatest in the high planting density (Stiptsov and Botev, 1995).

2.4. RADIATION ENVIRONMENT

The radiation regime within a tree crown varies with space and time like many other physical phenomena. Its spatial variation is determined by the crown structure and incident radiation which fluctuates during the day and therefore induces the temporal change in the radiation regime within the tree crown. Photosynthesis and transpiration of a leaf are nonlinearly related to the radiation flux density absorbed by the leaf and they are overestimated if the radiation flux density is averaged over both a large spatial area and long period of time (Smolander and Lappi, 1985).

2.4.1. Influence of crown shape on photosynthetically active radiation (PAR)

Biomass production under a given set of conditions is related to the amount of light intercepted by the canopies (Cannel, 1983; Kuppers, 1994; Beadle, 1997). The size and arrangement of plant canopies determines the amount of light which they intercept (Caldwell *et al.,* 1986; Beadle, 1997; Valladares, 1999).

Several studies have been made on the influence of crown shape on PAR absorption (Jahnke and Lawrence, 1965; Terjung and Louie, 1972; Oker-Blom and Kellomaki 1988; Kuuluvainen and Pukkula, 1987). Photosynthetic rate of a tree crown depends not only on the flux density of incident PAR but also on the PAR regime, which may be affected by the crown shape.

The influence of crown shape on PAR absorption, photosynthesis, and transpiration may depend on tree spacing (Kuuluvainen and Pukkula, 1987). It was proved in a study that when the tree spacing is wider (10×10 m), the narrowest crown has the largest daily amounts of both PAR absorbed and photosynthesis. This is because the crown surface area of the narrowest crown is largest. Consequently, larger crown has the smallest daily amounts of both PAR absorbed and photosynthesis. This is consistent with the conclusions of Oker-Blom and KellomSki (1988) that either a vertically or a horizontally extended crown absorbs a larger amount of PAR than one that is intermediate in shape.

In closer spacing, the flattest tree crown has the largest daily amounts of both PAR absorbed and photosynthesis. The relative differences are less than 10 % for the daily amount of PAR absorbed and less than 15 % for the daily amount of photosynthesis among the tree crowns of different shapes, over the range of tree spacing studied. This is because a canopy made up of flat crowns is more uniform in the horizontal plane and therefore more PAR will be absorbed, with the result that the daily amount of photosynthesis is also largest (Mann *et al.*, 1979).

Contrary to this, the crown shape was found to have only a small influence (less than 5%) on the daily amounts of both PAR absorbed and photosynthesis over the range of stocking density from 700 to 2500 trees/ha which is similar with other simulation studies (Oker-Blom and Kellomaki, 1988) but the influence of crown shape on PAR absorption, depend on tree spacing (Kuuluvainen and Pukkula, 1987).

2.4.2. Planting density and PAR

Canopy structure, stand density, row orientation, leaf area index, site, latitude, season and spectral quality of light are major factors that decide the extent of solar radiation entering into the understorey of plantation (Baldocchi and Ollineau, 1994). Among them, the planting density play an important role on the quality and quantity of under storey PAR availability.

For instance, the PAR transmittance beneath the canopy was 90% in the lowest planting density (Starostin and Maslakov, 1989). Modification in crown geometry as contributed by the variation in spacing may also modify the understorey light environment. However, information on such relationship is limited for tropical fast growing species.

Initial planting density has profound influence on the understorey PAR availability. Variation in the canopy structure between species and consequent changes in the PAR interception has been observed. For instance, Kumar *et al.* (2001) in an experiment involving four MPTS and grass species, observed strong interspecific differences in the understorey PAR with *A. auriculiformis* intercepting much of solar radiation while the *Ailanthus triphysa* intercepted least. A study in loblolly pine (*Pinus taeda*) plantation reported that intercepted PAR was significantly greater for stands planted at higher densities, while live crown length and crown ratio were significantly greater for stands planted at the lower densities, supporting the idea that higher density stands can intercept PAR more efficiently than lower density stands (Akers *et al.,* 2013).

Accieresi and Ansin (1994) conducted a study on effect of planting density on light penetration and forage production in a poplar based agroforestry system and reported that light penetration and forage production reduced with an increase in stand density. Similarly, another study on the effect of different stocking level and fertilizer regimes on the growth of *Ailanthus excelsa,* grown at four densities revealed that mean PAR transmittance (72 %) was greater for the lowest stand density. This suggests that plantation of high density intercepts substantially more radiation than the low density (Kumar *et al.,* 2001). As leaf area develops, the radiation interception by leaves increases. The LAI was higher for the *Acacia mangium* than for *Acacia auriculiformis* because the leaf area is larger for mangium and therefore it produces a denser canopy and greater shading (Mathew *et al.,* 1992).

Density manipulation through thinning in the seven year old *A. mangium* stand revealed that PAR transmitted to understorey ranged between 7% (unthinned) and 61% (heavily thinned) indicating that the unthinned *A. mangium* canopy absorb more radiation than transmission due to the larger canopy (Kunhamu *et al.,* 2008). Acacia with spreading, dense crown absorb high amount of radiation (Norisada *et al.,* 2005). Kumar *et al.* (2000) reported that the *A. auriculiformis* characterized by dense or deep canopy intercept more light while casuarina, where its needles like cladophylls leads to great light penetration into the soil surface.

2.4.3 Pruning and PAR

Tree pruning is an important silvicultural operation which helps in improving the understorey light environment. In many studies, it was observed that pruning temporarily open up the canopy and significantly improve the photosynthetic flux density at stand level. Pruning intensity affect the amount of PAR transmission in plantation. A study on effect of different pruning intensity on MPT'S shown that maximum PAR transmission were recorded for the 75% pruning treatment and it was minimum for the 10% pruning treatment under rainfed conditions (Handa *et al.,* 2007). Similarly, pruning increased PAR beneath the pruned trees in a high density walnut plantation (Shangwei *et al.,* 2009). A study in a nine year old stand of *Pinus radiata* indicated that unthinned pruned stands can intercept up to 25% more PAR than the unpruned thinned stands with the same leaf area index (Grace *et al.,* 1987).

2.5. PLANTING DENSITY AND TREE GROWTH

A knowledge about the optimum space requirements of trees is essential for the effective utilization of available resources, which in turn determines the productivity as well as product quality in trees (Mead and Speechly, 1991). Silvicultural prescriptions involving the stand density are often made based on the assumption that at higher stocking levels, individual tree productivity is inversely related to planting density (Smith *et al.,* 1997).

Many sources indicate that height growth is insensitive to density and that radial growth increases with increased spacing (Lanner, 1985). However, a few detailed studies showed that in very young forest plantations, planting at high densities show more rapid growth than those planted at lower densities. For example, annual height growth has been shown to be positively correlated with stocking density at a young age for several broad-leaved species and coniferous trees (Helmers, 1948; De Bell and Giordano, 1994; Gilbert *et al.,* 1995; Knowe and Hibbs, 1996; Ritchie, 1997).

Contrary to height growth observations, in general, radial growth increased with decreasing plant density and lowest density showed consistently higher GBH. Practically, in all experiments, the mean diameter for trees in the stand increases with increasing spacing (Smith, 1997). However, the magnitude of response varies with the species and growth phase of stand. Differences on account of variation in the population density were significantly observed from two years onwards by Kunhamu *et al.* (2005) in an *Acacia mangium* stand at varying densities. Contrary to the above studies, Cameron and Penna (1988) found increased diameter growth with an increased stocking density in their study of *Eucalyptus grandis*.

2.6. PRUNING AND TREE GROWTH

Tree pruning increases the amount of clear wood produced by a tree. Pruning achieves this by removing branches sufficiently early and containing branch defects to a small central knotty core (Washusen *et al.,* 2000). In pruning trial of *Acacia mangium*, Majid and Paudyal (1992) observed that significant differences in the diameter growth was observed when crown removal was more than 40 % and also it has significant effect on tapering of stem. Tree pruning generally showed a reduction in the growth implying that *Acacia mangium* might respond better at relatively lower pruning intensities (Kunhamu, 2006). Study by Tuomela *et al.* (1996) reported that the growth of *Acacia mangium* after pruning was decreased about 70 % compared to the unpruned plots.

It is clear from many studies that the minimum level of pruning that affects growth varies between the species, and this level needs to be identified before the appropriate pruning prescriptions can be developed. For example, the growth of *Pinus patula* was reduced by removal of more than 25% of the lower green crown length (Karani, 1978). Sugi (*Cryptomeria japonica*) was found to withstand slightly higher levels of pruning (30% of lower green crown length) (Dakin, 1982) and in *Acacia mangium,* the growth was only affected if pruning removed more than 40% of lower green crown length (Majid and Paudyal, 1992).

2.7. STAND LEAF AREA INDEX (LAI)

Crown dimensions, tree phenology and leaf density affect the use of available resources and competition between trees which in turn improve yield and overall productivity in tree based systems (Cannel, 1983). So the factors like LAI and crown development are most important for standardization of spacing in plantations. In bamboo based agroforestry system, LAI of bamboo was significantly decreased with decrease in stand density (Bhimappa, 2014). The higher LAI may distress growth in tree based systems. Low understorey PAR levels resulting from high level of LAI decreased the growth of plants in a wheat based agroforestry systems (Chirko *et al.,* 1999). Greater light extinction when stand LAI is more has been reported by Kumar *et al.* (2001). The information on LAI and PAR are indispensable for optimizing productivity in the tree based systems. In eucalypt plantations, LAI increases as stands develop and then tends to stabilize or decline only slowly, effectively achieving a steady-state or equilibrium (e.g., Hingston *et al.*, 1994). Theoretical analyses suggest that the equilibrium LAI of a plantation depends in part on factors that affect the light utilization efficiency and respiratory rate of foliage (Dewar, 1996). This is supported by data on the responses of LAI to nutrition and soil water (Fassnacht and Gower, 1997) and temperature (Ryan *et al.*, 1994).

Both evaporation and transpiration dissipate heat. **Shashua-Bar and Hoffman (2000)** found that a partial shaded area (PSA) under the tree canopy was a major factor to determine the microclimate effect of the tree and they used PSA in estimating the effect of trees on the contribution of direct solar radiation to air temperature variances. LAI represents foliage density, which includes not only PSA but also leaf area, which includes the multilayers of leaves forming the canopy.

Canopies with the high LAI absorb more momentum and therefore allow less vertical mixing of air within the canopy (Raupach *et al.,* 1996) and thus act to keep the near-surface air cool and increases humidity. Canopies with the lower LAI allow more turbulent mixing of air within the canopy sub-layer, which in turn allow more light to reach the surface and this results in air temperature increase more rapidly and reaches a higher maximum value than the denser canopies.

Under the low LAI canopies, where the daytime temperature is higher, the vapour pressure deficit (VPD) is also larger, while the relative humidity is lower. As the VPD increases, evapotranspiration also increases as the air has an increased capacity to hold water vapour, creating a larger potential gradient across the leaf-air and soil-air boundaries (Garratt, 1992). This increases the transpiration in the low LAI canopies. The high LAI canopies have a smaller specific humidity than the low LAI canopies. This finding is similar to that reported by Law *et al.* (2001) from the observations of temperate forests.

2.8. WATER USE EFFICIENCY (WUE)

Water use efficiency is expressed as assimilation production per unit of water consumption. As an important index for plant energy conversion, WUE has been applied widely in many fields. Water use efficiency is also referred as rate of carbon uptake per unit of water lost. It integrates a suite of biotic and abiotic factors, and importantly, quantifies how much water a tree uses relative to the carbon gained.

Water use efficiency describes a tree's photosynthetic production rate relative to the rate at which it transpires water to the atmosphere. It is a measure of plant performance that has long been of interest to the foresters, agronomists and ecologists (Bacon, 2004). In cropping systems, improving the water use efficiency presents a means of increasing biomass production in the face of finite water supplies. In forestry systems, water use efficiency is a critical link between the wood production and water management.

2.8.1. Carbon isotope discrimination (δ) and water use efficiency (WUE)

Carbon isotope discrimination has been proposed as a method and technique for evaluating and improving WUE in C_3 plants (Ehleringer and Cooper, 1986; Martin and Thorstenson, 1988). WUE may be estimated as the ratio of dry matter accumulation over time to amount of water transpired (transpiration efficiency (TE)) or as the ratio of CO_2 assimilation to stomatal conductance or transpiration (WUE of gas exchange or instantaneous WUE).

Carbon isotope ratios are well established indicators of plant WUE. It is relevant to WUE via extent of stomatal conductance and capacity of CO_2 fixation during photosynthesis. In C_3 species, the isotopic ratio of heavy isotope of carbon (^{13}C) to ^{12}C in plant materials is less than the isotopic ratio of ^{13}C to ^{12}C in the atmosphere, indicating that plants discriminate against ^{13}C during photosynthesis which leads to a depletion of the plant dry matter in^{13}C.

This process depends on the ratio of the intercellular to atmospheric CO_2 concentration (*Ci*/Ca) which is linked to stomatal conductance (Farquhar *et al.*, 1982). Increasing CO_2 assimilation or decreasing stomatal conductance results in increasing WUE and declining of leaf intercellular CO_2 (*Ci*) and consequently Δ. Therefore, there should be a negative relationship between WUE and Δ due to the independent relation between *Ci* and Δ or WUE (Farquhar *et al.*, 1982 and Farquhar and Richards, 1984).

Farquhar *et al.* (1982) proved that leaf-to-air vapour pressure deficit (D) of dry matter in plant photosynthetic products is significantly correlated with the Pi/Pa ratio. In a study of *Acacia mangium*, the isotope effect on diffusion of atmospheric CO_2 via stomata was denoted by a = 4.6 ‰ and that in net C3 diffusion with respect to Pi was indicated by b = 28.2 ‰ which fitted with the values of WUE calculated from the gas exchange method. A gas exchange system is often employed to measure the leaf WUE, but it fails when it is measured on a larger scale in the fields (Farquhar *et al.*, 1989). Thus, the application of stable carbon isotope discrimination in estimating the water use efficiency would reduce the effects of fluctuating environmental factors during the synthesis of dry matter, and improve the ecophysiological studies on carbon and water balance when scaling from the plant to canopy in the fields.

2.8.2. Factors affecting water use efficiency (WUE)

Water use efficiency is influenced by solar radiation, ambient CO_2, silvicultural practices and other environmental factors. Egli *et al.* (1998) reported that WUE of plants was increased mostly by decreasing stomatal conductance. In contrast, WUE of plants were decreased with increase in stomatal conductance (Stanciel *et al.*, 2000).

Many studies have been carried out on effect of CO_2 on WUE showing increase in WUE by 50-150% at doubled CO_2 concentrations mainly because of increase in photosynthesis and decrease in transpiration with increasing CO_2 concentrations (Serraj *et al.*, 1999).

The effect of silvicultural practices like thinning, pruning, fertilizer application have different effect on WUE. For example, the effect of fertiliser or site quality on the WUE appears to be species and site specific with reports of increase (Stape *et al.,* 2004) or no changes in the WUE (Husband *et al.,* 2004). Thinning has been reported to decrease WUE due to the increased transpiration (Breda *et al.,* 1995).

In addition to these factors, a number of other factors, both environmental and biotic, could affect the WUE. These include climate change, nitrogen deposition, changes in leaf area, canopy height, surface roughness and coupling of the canopy to the atmosphere and long term instrument drift (Keenan *et al.,* 2013). Photosynthesis is the primary driver for plant production, evolution, and global carbon cycle, while transpiration drives water cycle in soil-plant-atmosphere continuum (SPAC).

2.8.3. Effect of carbon dioxide on water use efficiency (WUE)

As the atmospheric CO_2 content rises, most plants exhibit the increased rates of net photosynthesis and biomass production. Moreover, on a per unit leaf area basis, they typically lose less water via transpiration (Saxe *et al.,* 1998; Seneweera *et al.,* 1998; Sgherri *et al.,* 1998; Smart *et al.,* 1998; Tognetti *et al.,* 1998; Wayne *et al.,* 1998; Centritto *et al.,* 1999; Serraj *et al.,* 1999), as leaves tend to display lower stomatal conductance at elevated atmospheric CO_2 concentrations (Egli *et al.*, 1998; Garcia *et al.*, 1998; Lecain and Morgan, 1998; Tjoelker *et al.*, 1998; Leymarie *et al.,* 1999; Runion *et al.,* 1999; Stanciel *et al.,* 2000). Consequently, the plant water use efficiency or the amount of carbon gained per unit of water lost per unit leaf area should increase dramatically as the atmospheric CO_2 content rises.

In Netherlands, plants that were subjected to an atmospheric CO_2 concentration of 566 ppm exhibited greater water use efficiencies than control plants fumigated with air of 354 ppm CO_2 (Sgherri *et al.*, 1998). Likewise, in a study performed by Tjoelker *et al.* (1998), seedlings of quaking aspen, paper birch, tamarack, black spruce and jack pine grown at 580 ppm CO_2 for three months showed that all plants displayed increase in water use efficiency, ranging from 40 to 80%. A study conducted by Centritto *et al.* (1999), cherry seedlings grown at twice-ambient levels of atmospheric CO_2 displayed water use efficiency showed that these were 50% greater WUE than those of ambient controls, regardless of soil moisture status.

Wayne *et al.* (1998), concluded that the yellow birch seedlings grown at 800 ppm CO_2 had water use efficiencies that were 52 % and 94% greater than the control plants subjected to low and high air temperatures regime, respectively. Other trees that have been found to be benefited by extra carbon dioxide are longleaf pine (Runion *et al.,* 1999), red oak (Anderson and Tomlinson, 1998), silver birch (Rey and Jarvis, 1998), beech (Egli *et al.*, 1998) and spruce (Roberntz and Stockfors, 1998).

Contrary to the above studies, the WUE has been reported to decrease with an increase in CO_2. Akther et al. (2005) indicated that the increase of atmospheric CO_2 concentration for a short period of time caused the stomata to close, and then the concentration of cellular CO_2 increased, made the Ci/Ca ratio or Pi/Pa ratio change, where the leaf to air vapour deficit increased and the WUE declined. Comstock and Ehleringer (1993) also found that increase of atmospheric CO_2 concentration for a longer period of time with fluctuation of leaf temperature would influence the WUE.

There has not been a conclusion on the reason for the increasing WUE with elevated CO_2 concentrations. However, Saxe *et al.* (1998) reported that increase in the photosynthesis with elevated CO_2 was the main reason for increase in WUE.

It is also proved in almost all the experiments, photosynthesis increased with increasing CO_2 concentrations and then it appeared to decline, which was mainly caused by accumulation of photosynthates. On the other hand, stomatal conductance is an important index that show sensitive responses to the elevated CO_2 concentrations, i.e., stomatal conductance decreases with the elevated CO_2 concentration and maintains lower intercellular CO_2 pressure by 20-30 % than atmospheric CO_2 concentration. Under doubled CO_2 concentration conditions, 33-50 % or more of the stomatal resistance was increased. The decrease in stomatal conductance can reduce the transpiration rate and thus contribute to increases in the WUE.

2.8.4. Planting density and water use efficiency (WUE)

Planting density was found to affect the growth-related traits. The effect of planting density on tree physiology is fundamentally mediated by competition for resource acquisition, including light, water and nutrients (Benomar *et al.,* 2011; Bullard *et al.,* 2002; De Bell *et al.,* 1996; Green *et al.,* 2001). It has been found that the effect of planting density on WUE of tree depend on the site characteristics in terms of soil fertility and water availability.

Specifically, when soil conditions are favourable in terms of water and nutrients, increase in spacing would primarily accentuate plant competition for light leading to decrease in WUE followed by decrease in net assimilation rates due to light limitation (Buchman *et al.,* 1997). In contrast, when soil conditions are limited for water and nutrients, growth would be reduced and increased spacing would primarily accentuate plant competition for soil resources leading to increase in WUE as a consequence of water limitation (Chamaillard *et al.,* 2011).

To our knowledge, the effect of planting density on WUE has not been directly addressed in *Acacia mangium* so far. Data on other species remain limited and varied with tree age, planting densities, system designs, and the way WUE is assessed.

Benomar *et al.* (2011) conducted a study on the poplar genotypes and found that light-saturated photosynthesis rates of trees grown at the closest spacing (10,000 trees per ha) were lower than those of trees grown at the wider spacing (400–1100 trees per ha). No significant effect was observed for the stomatal conductance suggesting that the intrinsic water-use efficiency was actually lower at the high planting density. A study in a one year old *Eucalyptus grandis* trees planted at a density of 2150 ha^{-1} exhibited the higher transpiration efficiency than those planted at a density of 304 or 82 ha^{-1} (Eastham *et al.,* 1990). Higher WUE estimates associated with the higher tree density have been similarly reported for a one year old seedlings of *Betula albosinensis* (Zhang *et al.,* 2008), 5 year old trees of *Pinus halepensis* (Querejeta *et al.,* 2008) and 250 year old trees of *Pinus ponderosa* (McDowell *et al.,* 2003).

Opposite trends have however been reported for a six year old trees of *Pinus radiata* (Walcroft *et al.,* 1996), four year old trees of *Pinus pinaster* (Warren *et al.,* 2001) and thirty-one year old *Pinus nigra* trees (Martin-benito *et al.,* 2010). In a study of *Pinus caribaea* planted at different densities, the WUE is more at density of 63/m^2 and this indicates that optimal density needed to achieve the greater water use efficiency (Ghosh, and Dabral, 1980). However, the WUE not affected by planting density have been reported for birch seedlings, which were grown under the elevated CO_2 at different planting densities (Garcia *et al.,* 1998).

2.8.5. Pruning and water use efficiency (WUE)

The study shows that the silvicultural treatments such as pruning may not only reduce the water use by reducing the stand leaf area but also by increasing the efficiency with which water is used to produce the wood. Thus, in addition to improving the growth rates, these treatments may also be used to reduce the water use and drought susceptibility of plantations while making more efficient use of the water that is transpired (White *et al.,* 2009).

A study conducted in a three year old eucalyptus plantation revealed that pruning increases the WUE by 21 % as compared to the unpruned trees due to the removal of shade and least efficient canopy foliage (Forrester *et al.,* 2012). In a runoff agroforestry system in arid environment, the highest values of WUE was seen associated with the pruned trees at high density (1.59 kg m^{-3}) as compared to the unpruned trees at high density (0.8 kg m^{-3}) (Dropplermann *et al.,* 2000). Similarly, in another run-off agroforestry experiment conducted in Israel with *Acacia saligna,* concluded that WUE of the unpruned trees were approximately twice as high as that of the pruned trees (Degen and Berliner, 1997).

In contrast to above studies, a five year old *Acacia melanoxylon* plantation did not show any changes in the photosynthetic rate on WUE after pruning (Medhurst and Beadle, 2005). However, more studies are required to examine how the magnitude and duration of pruning effects on water use efficiency vary between planting density, resource availabilities and climatic conditions.

Materials and Methods

3. MATERIALS AND METHODS

3.1. LOCATION

The study was conducted at Livestock Research Station (LRS), Thiruvizhamkunnu, Palakkad district in Kerala located at 11^0 21’30’’ N latitude, 76^0 21’50’’ E longitude and 60-70 m above mean sea level. The *Acacia mangium* Willd. stand was established during the year 2000 with the objective of studying the effect of planting density and pruning on growth and form of trees.

3.2. WEATHER PARAMETERS

Table 1. Weather parameters during the experimental period (December 2014 to November 2015) at Thiruvizhamkunnu, Kerala, India

Month	Maximum temperature (^{0} C)	Minimum temperature (^{0} C)	Maximum relative humidity (%)	Minimum relative humidity (%)	Total rainfall (mm)
December	33.23	16.48	100	42	37.4
January	33.68	14.84	100	29	8.2
February	36.02	15.29	100	10	1.4
March	38.61	20.04	100	12	5.9
April	37.62	20.98	100	41	132.7
May	34.43	20.95	100	51	253.4
June	33.75	22.02	100	59	207.8
July	32.14	21.56	100	66	206.2
September	33.45	21.75	100	65	302.5
October	34.23	21.41	100	45	263.9
November	33.26	19.88	100	53	151.5

The above data was collected from the weather station maintained by the Livestock Research Station, Thiruvizhamkunnu.

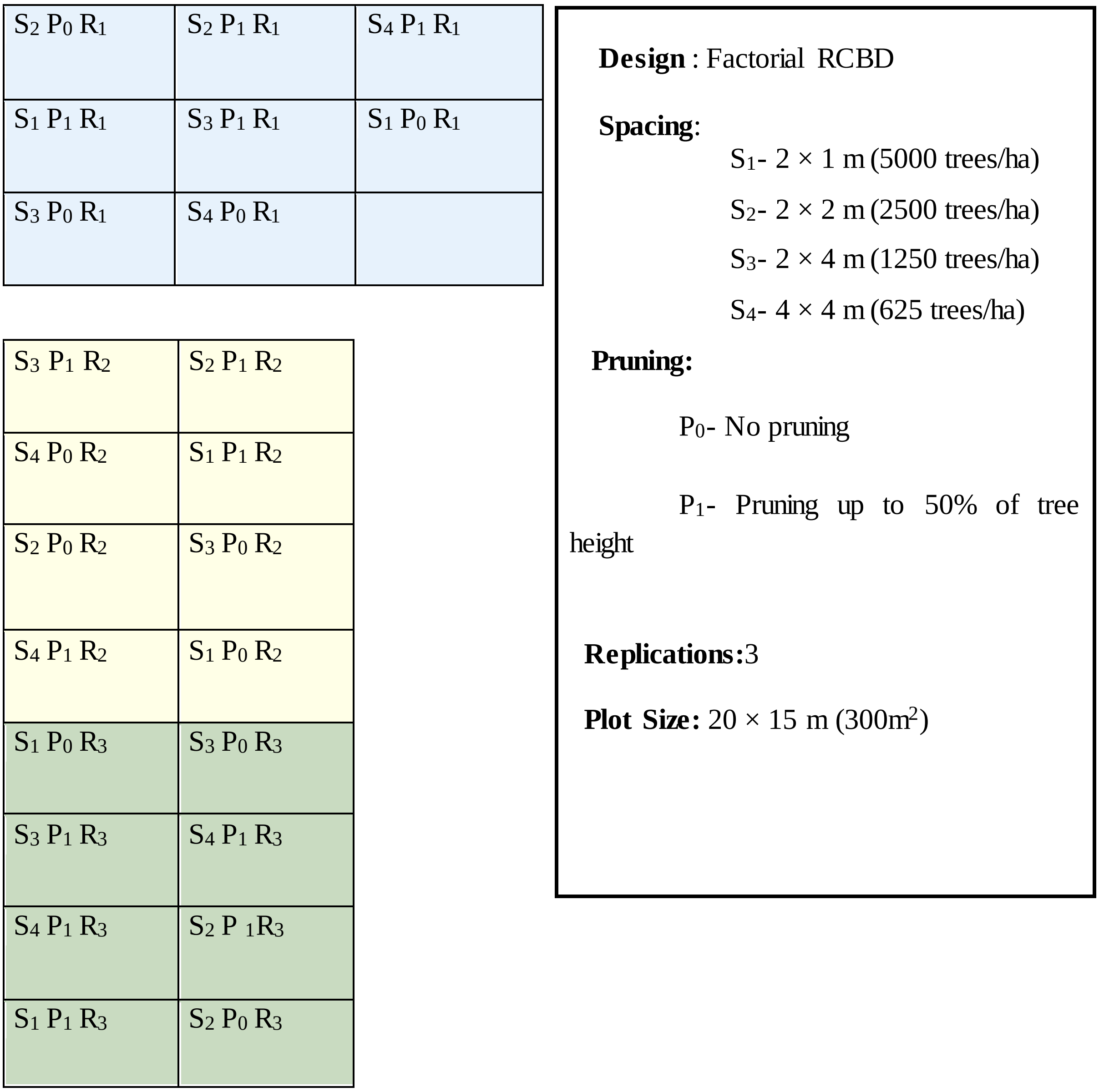
Table 1 shows the weather parameters during the study period collected from a weather station adjoining the *Acacia mangium* plantation studied. The area receives rainfall by south-west monsoon from June to September. The dry period, from January to March, is characterised by no rainfall. The temperature recordings showed that March to be the hottest month with the maximum temperature going up to 38° C. The relative humidity showed the low values when compared to Kerala in general. The pre-monsoon showers mostly falling in April and May contributed little to the total rainfall.

3.3. SOIL

The soil of experimental site is of lateritic origin (ultisol) with an average pH of 5.4 and bulk density of 0.86 g/ cm^3 (Kunhamu *et al.*, 2005).

3.4. FIELD LAYOUT

The experiment was laid out as a two factor factorial RBD with three replications. The experimental plot size was 20 x15 m (300 m^2) with four different spacing i.e., S_1-2×1 m, S_2-2×2 m, S_3-2×4 m, S_4 -4×4 m and two levels of pruning i.e., No pruning (P_0), pruning up to 50% of tree height (P_1). The layout of experimental plot is shown (Fig 1)



$S_2 P_0 R_1$	$S_2 P_1 R_1$	$S_4 P_1 R_1$
$S_1 P_1 R_1$	$S_3 P_1 R_1$	$S_1 P_0 R_1$
$S_3 P_0 R_1$	$S_4 P_0 R_1$	

$S_3 P_1 R_2$	$S_2 P_1 R_2$
$S_4 P_0 R_2$	$S_1 P_1 R_2$
$S_2 P_0 R_2$	$S_3 P_0 R_2$
$S_4 P_1 R_2$	$S_1 P_0 R_2$
$S_1 P_0 R_3$	$S_3 P_0 R_3$
$S_3 P_1 R_3$	$S_4 P_1 R_3$
$S_4 P_1 R_3$	$S_2 P_1 R_3$
$S_1 P_1 R_3$	$S_2 P_0 R_3$

Design : Factorial RCBD

Spacing:

S_1- 2 × 1 m (5000 trees/ha)

S_2- 2 × 2 m (2500 trees/ha)

S_3- 2 × 4 m (1250 trees/ha)

S_4- 4 × 4 m (625 trees/ha)

Pruning:

P_0- No pruning

P_1- Pruning up to 50% of tree height

Replications:3

Plot Size: 20 × 15 m (300m^2)

Fig 1. Experimental layout of *Acacia mangium* stand showing different planting density and pruning treatments at Thiruvizhamkunnu, Kerala.


A


B

Plate 1. Experimental plot of *Acacia mangium* stand showing various planting density treatments: (A) 5000 trees/ha (B) 2500 trees/ha (C) 1250 trees/ha (D) 625 trees/ha

3.5.1 Air temperature (AT)

A portable iron tower capable of lifting sensors was fabricated and installed in the different planting densities of plantation to take measurements at the height of 5 and 10 m above the ground level using the temperature sensors (EMCON Pvt Ltd, Cochin).

3.5.2. Canopy-air temperature difference (CATD)

CATD was measured using handheld infrared thermometer (AGRITHERM-III 6110.42L). Temperature measurements were done after 11:00 AM, a time when difference between stressed and non-stressed plants are most readily detected (Gardner *et al.*, 1981). Leaves that are fully expanded and completely exposed to sunlight were selected for temperature measurements.

3.5.3. Soil temperature (ST)

Soil temperature was measured at a depth of 5 cm, 10 cm, and 20 cm from the soil surface in each plot using a soil temperature sensor (EMCON Pvt Ltd, Cochin).

3.6. MOISTURE ENVIRONMENT

3.6.1. Relative humidity (RH)

A portable iron tower capable of lifting sensors was fabricated and installed in the different planting densities of plantation to take measurements at the height of 5 and 10 m above the ground level using the relative humidity sensors (EMCON Pvt Ltd, Cochin).

3.6.2. Soil moisture content (SMC)

Soil moisture was measured gravimetrically from each plot of *Acacia mangium* stand and also from treeless control plots. Soil samples were taken at a depth of 5 cm, 10 cm, 20 cm and 30 cm from the soil surface using a soil auger.

Plate 2. Micrometeological stand fabricated to take measurement at different heights above the ground level

Plate 3. Sensors (Emcon Pvt. Ltd, Cochin) used for measurement of temperature, humidity and PAR

Plate 4. Data Logger (Emcon Pvt. Ltd, Cochin)

Plate 5. Soil temperature sensor (Emcon Pvt. Ltd, Cochin) used for measurement of soil temperature

These soil samples were then transferred to the moisture cans and these cans were closed to prevent the loss of moisture by evaporation. The cans containing moist soil were weighed immediately in the field to record the fresh weight. Then these samples were carried to the laboratory and kept in a hot air oven at 105° C till the constant weight is attained. After this, the dry weight of samples were recorded. From the difference in weight, the moisture content in soil is expressed as percent on oven dry basis.

$$\text{Moisture (\%) in the soil} = \frac{\text{Weight of moisture in the sample}}{\text{Weight of oven dry sample}} \times 100$$

3.6.3. Relative water content (RWC)

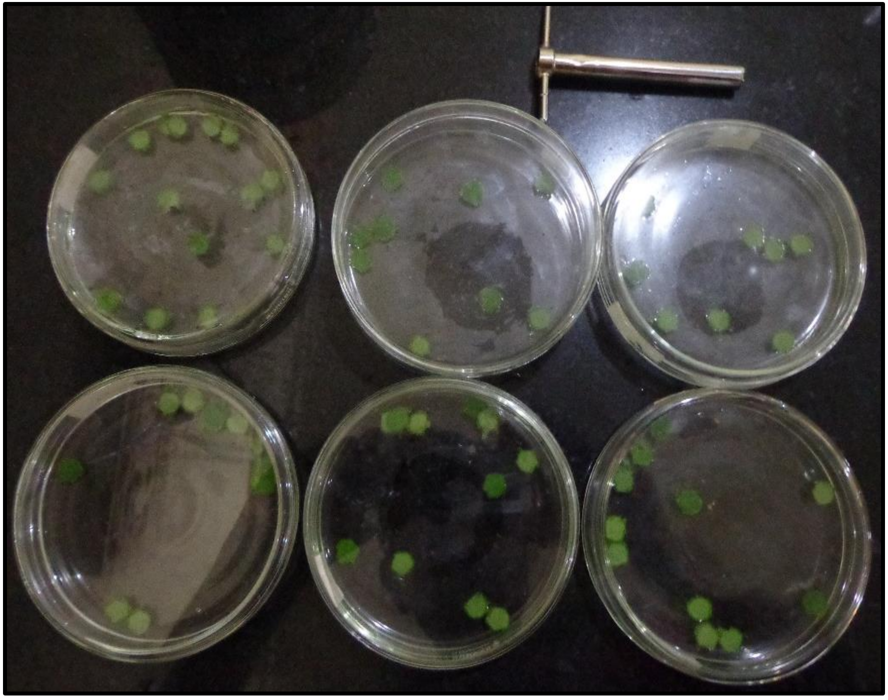
Relative water content was measured from leaves selected at random from each of the experimental plot. The leaves were placed in polyethene bags and taken to the laboratory. The leaf discs were cut from the leaves using a cork borer and weighed using sensitive balance up to three decimal. The leaf discs were then hydrated to full turgidity by floating the leaf discs on distilled water in closed petri dish for 24 hours. Leaf discs removed from the water were wiped and weighed with the same balance, then the turgid weight was obtained. Leaves were then dried in an oven at 80° C for 48 hours to determine the dry weight. RWC was calculated using the below equation.

$$\text{RWC (\%)} = \frac{(\text{Fresh weight} - \text{Dry weight})}{(\text{Turgid weight} - \text{Dry weight})} \times 100$$

3.6.4. Evapotranspiration (ET)

The evapotranspiration rate for each plot was calculated using FAO modified Penman-Monteith equation (Allen *et al.*, 1998).

Plate 6. Collections of soil samples for estimation of soil moisture content



3.7. RADIATION ENVIRONMENT

3.7.1. Photosynthetically active radiation (PAR)

A portable iron tower capable of lifting sensors was fabricated and installed in the different planting densities of plantation to take measurements at the height of 5 and 10 m above the ground level using the PAR sensors (EMCON Pvt Ltd, Cochin).

Diurnal variation of PAR below the canopy and above the canopy was measured using a line quantum sensor at hourly intervals. Within each plot, PAR was measured using a line quantum sensor which was installed at the centre of plot at a height of 60 cm from the ground level. Radiation incident over the canopy was simultaneously recorded by another line quantum sensor, which kept on open space near to the field. PAR transmittance through the canopy was determined using the equation.

$$T_c = \frac{K\downarrow \text{sub-canopy}}{K\downarrow \text{above}}$$

Where, T_c - Canopy PAR transmittance

$K\downarrow$ - Measured incoming solar radiation

3.7.2. Light extinction coefficient

The light extinction coefficient was calculated from the Lambert-Beer's law, the average extinction coefficient (K) was obtained using the below equation

$$K = -\frac{\ln (PAR_t) / (PAR_i)}{LAI}$$

Where,

K - Light extinction coefficient

PAR_t - Transmitted PAR through the canopy

PAR_i- PAR incident on the stand

LAI - Leaf area index

ln - Natural logarithm

3.8. BIOMETRIC OBSERVATIONS

3.8.1. Height

Height of trees were measured from the base of tree to growing tip with the help of Haga altimeter.

3.8.2. Diameter

Diameter of trees were measured at breast height (1.37 m).

3.8.3. Stand leaf area index (LAI)

LAI of each plot was estimated by a canopy analyser (LAI-2000, LI-COR Inc., Nebraska, and USA). The canopy analyser, which indirectly measures the LAI of canopies based on the relationship between leaf area and canopy transmittance (Sternberg *et al.*, 1994).

3.8.4. Aboveground standing biomass

The aboveground biomass of the standing trees were computed using the below allometric equation (Kunhamu *et al.*, 2005).

$B=34.63-9.89\ (DBH)\ +0.887\ (DBH)^{2}\ (R^{2}=0.97)$

Where, B- total above ground biomass (kg tree^{-1})

DBH- diameter at breast height (1.37 m)

3.8.5. Collection of leaf samples and estimation of water use efficiency (WUE)

For the carbon isotope measurements, matured leaves from 10 to 15 m above the ground level from *Acacia mangium* stand was collected. The leaf samples were then oven-dried at 80° C for 48 hours. Dried leaf samples were then homogenized to a fine powder with a ball mill.

Plate 9. Canopy Analyser (LAI-2000, LI-COR Inc., Nebraska, USA) used for measurement of stand leaf area index

Plate 10. Observer in the field

Stable carbon isotope ratio was measured using an Isotope Ratio Mass Spectrometer (Delta plus, Thermo Fischer scientific, Bredmen, Germany) interfaced with an elemental analyser (NA112, Carlo-Erba, Italy) through a continuous flow device (Conflo-III, Thermo Fischer scientific), installed at the Department of Crop Physiology, UAS, Bengaluru. Carbon isotope discrimination ($\Delta^{13}C$), expressed in per mill (‰), was computed as per the notation proposed by (Farquhar et al., 1989).

$$\Delta^{13}C = (\delta^{13}C_a-\delta^{13}C_p)/ (1+\delta^{13}C_p/1000)$$

Where; $\delta^{13}C_a$ and $\delta^{13}C_p$ are the carbon isotope composition of atmospheric air and plant sample, respectively. The $\delta^{13}C_a$ was considered as -8‰ for the computation.

The analytical uncertainty was better than 0.15‰ which was determined by using an external standard calibrated against international standards such as ANU-Sucrose (Potato starch, Sigma-Aldrich δ^{13} = -26.85‰).

3.9. STATISTICAL ANALYSIS

The data were analysed using an ANOVA technique in SPSS (SPSS, INC, Chicago IL). All statistical tests were tested significant at $P<0.05$. Differences among the treatment means were determined using the Duncan Multiple Range Test. The Pearson correlation coefficient was used to detect relationships between the microclimate variables.

Results

4. RESULTS

The study involved the evaluation of the thermal, radiative, moisture regimes and water use efficiency under different planting densities and pruning levels in an *Acacia mangium* stand. Results of the investigations on microclimate variables, water use efficiency and growth parameters of an *Acacia mangium* stand are presented hereunder.

4.1. THERMAL ENVIRONMENT

4.1.1. Air temperature

The air temperature (AT) at the height of 5 m and 10 m above the ground level during the summer, pre-monsoon, monsoon and post-monsoon seasons are given in Table 2 and Fig. 2-3. The statistical analysis revealed significant differences between the AT of the open area (control) and *A.mangium* stand at different planting densities for all seasons except the monsoon season. It was also observed that AT values statistically differed among the various planting densities. In general, AT was higher during the summer season followed by pre-monsoon and post-monsoon season while lower AT was recorded during the monsoon season. In all seasons, the open area had higher air temperature compared to that of the plantation.

During the summer season, the higher AT values was found at density of 625 trees/ha (33.54 ° C and 33.67° C for 5 and 10 m height respectively) while the lower AT value was found at density of 5000 trees/ha (31° C and 30.61° C for 5 m and 10 m height respectively). The AT at the height of 5 and 10 m above the ground level did not show any significant differences between the planting densities of 5000 trees/ha and 2500 trees/ha and between 1250 trees /ha and 625 trees/ha. When compared to that of the open area (control), the percentage reduction in AT at the height of 5 and 10 m above the ground level was observed to be 12 % and 10 % under the closer spacing and 4% and 3 % under the wider spacing respectively.

Pruning had no significant effect on AT at the height of 5 and 10 m above the ground level. No significant differences were observed for planting density and pruning interactions.

During the pre-monsoon season, all planting densities showed significant differences with the open area except a density of 625 trees/ha. Among the planting densities, the higher value was recorded at density of 625 tree/ha (33.08° C and 33.14 ° C for 5 m and 10 m height respectively) while, the lower value was recorded at a density of 5000 trees/ha (30.74° C and 30.07° C for 5 m and 10 m height respectively). When compared to that of the open area (control), the percentage reduction in AT at the height of 5 and 10 m above ground was observed to be 12 % and 10 % under the closer spacing and 4% and 3 % under the wider spacing respectively. The AT value did not show any significant differences between the planting densities of 5000 trees/ha and 2500 trees/ha and between 1250 trees/ha and 625 trees/ha. Pruning had no significant effect on AT at the height of 5 m and 10 m above the ground level. No significant differences were observed for planting density and pruning interactions.

The AT patterns during the monsoon season followed a similar trend to that of previous seasons with the plantation having lower temperature compared to that of the open area. However, it did not vary among the planting densities. The values of AT from the high planting density to the low planting density varied from 28.38° C to 28.46 ° C at 5 m height and 28.72 ° C to 29.11 ° C at 10 m height above the ground level. Pruning had no significant effect on AT at the height of 5 and 10 m above the ground level. No significant differences were observed for planting density and pruning interactions.

During the post-monsoon season, it was found that AT significantly differed between the plantation of *Acacia mangium* and open area. Among the planting densities, the higher value was recorded at a density of 625 tree/ha (30.18 ° C and 31.01 ° C at 5 m and 10 m height respectively) while, the lower value was recorded at density of 5000 trees /ha (29.35° C and 29.95 ° C at 5 m and 10 m height respectively).

When compared to that of the open area (control), the percentage reduction at the height of 5 and 10 m above ground was observed to be 7 % and 9 % under the closer spacing and 4 % and 6 % under the wider spacing respectively. The AT in all planting densities except 625/ha were on par. Pruning had no significant effect on AT at the height of 5 and 10 m above the ground level. No significant differences were observed for planting density and pruning interactions.

Table 2. Air temperature at the height of 5 m and 10 m above the ground level in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

	Air temperature (° C)							
Planting density (trees/ha)	Summer		Pre-monsoon		Monsoon		Post-monsoon	
	5 m	10 m	5 m	10 m	5 m	10 m	5 m	10 m
5000	31.00^{d}	30.61^{d}	30.74^{d}	30.07^{d}	28.42^{b}	28.73^{b}	29.35^{c}	29.95^{c}
2500	31.59^{cd}	31.73^{cd}	31.88^{cd}	31.18^{cd}	28.47^{b}	28.85^{b}	29.82^{c}	30.15^{c}
1250	32.67^{bc}	32.68^{bc}	32.76^{bc}	32.16^{bc}	28.47^{b}	28.90^{b}	29.86^{c}	30.24^{c}
625	33.54^{b}	33.67^{b}	33.08^{ab}	33.14^{ab}	28.46^{b}	29.11^{b}	30.18^{b}	31.01^{b}
Open	35.80^{a}	35.80^{a}	34.50^{a}	34.50^{a}	30.58^{a}	30.58^{a}	32.26^{a}	32.26^{a}
Pruning								
Unpruned	31.74	31.81	31.86	32.04	28.89	28.42	30.20	29.71
50% pruning	32.60	32.59	31.39	32.40	28.91	28.52	30.47	29.89
Spacing and Pruning	ns	ns	ns	ns	ns	ns	ns	Ns

Values with same superscript do not differ significantly
ns-not significant

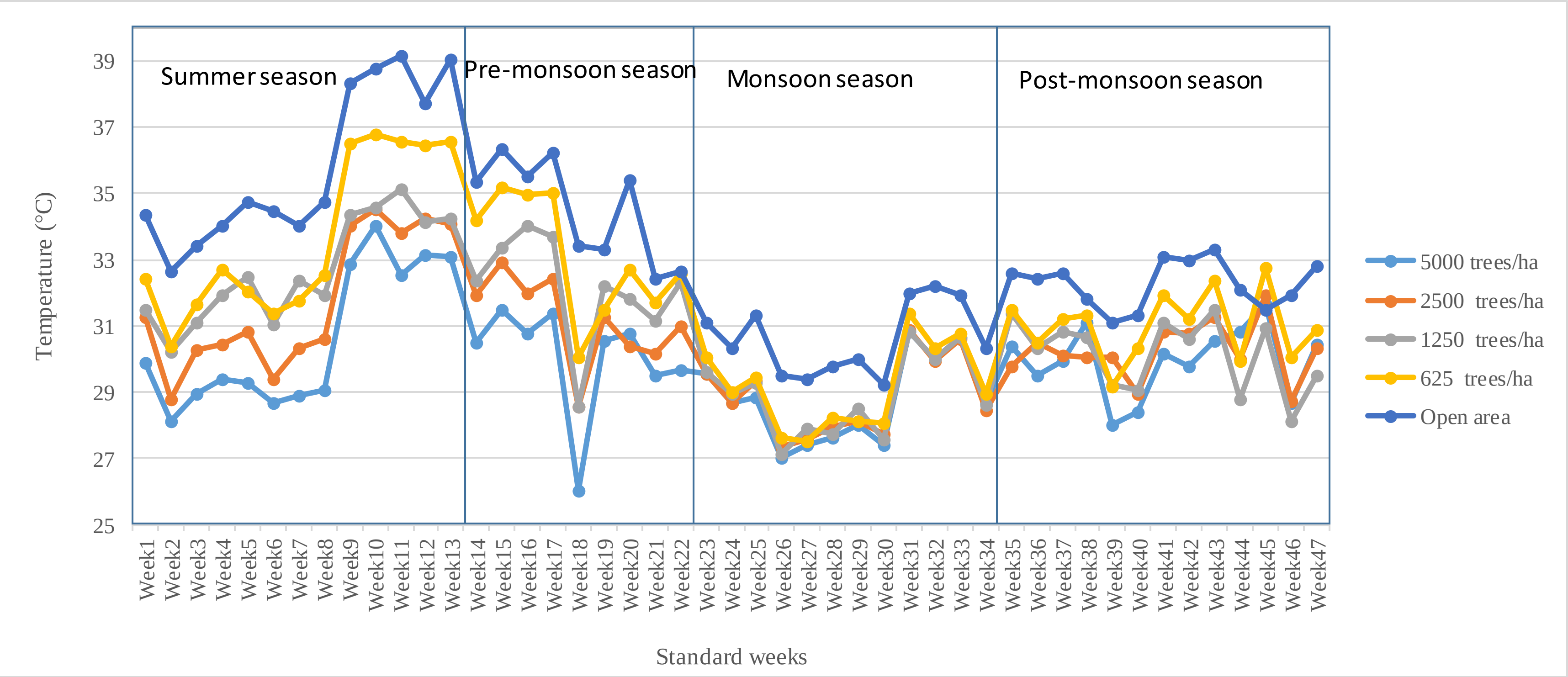


Fig 2. Weekly variation of air temperature at 5 m above the ground level in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

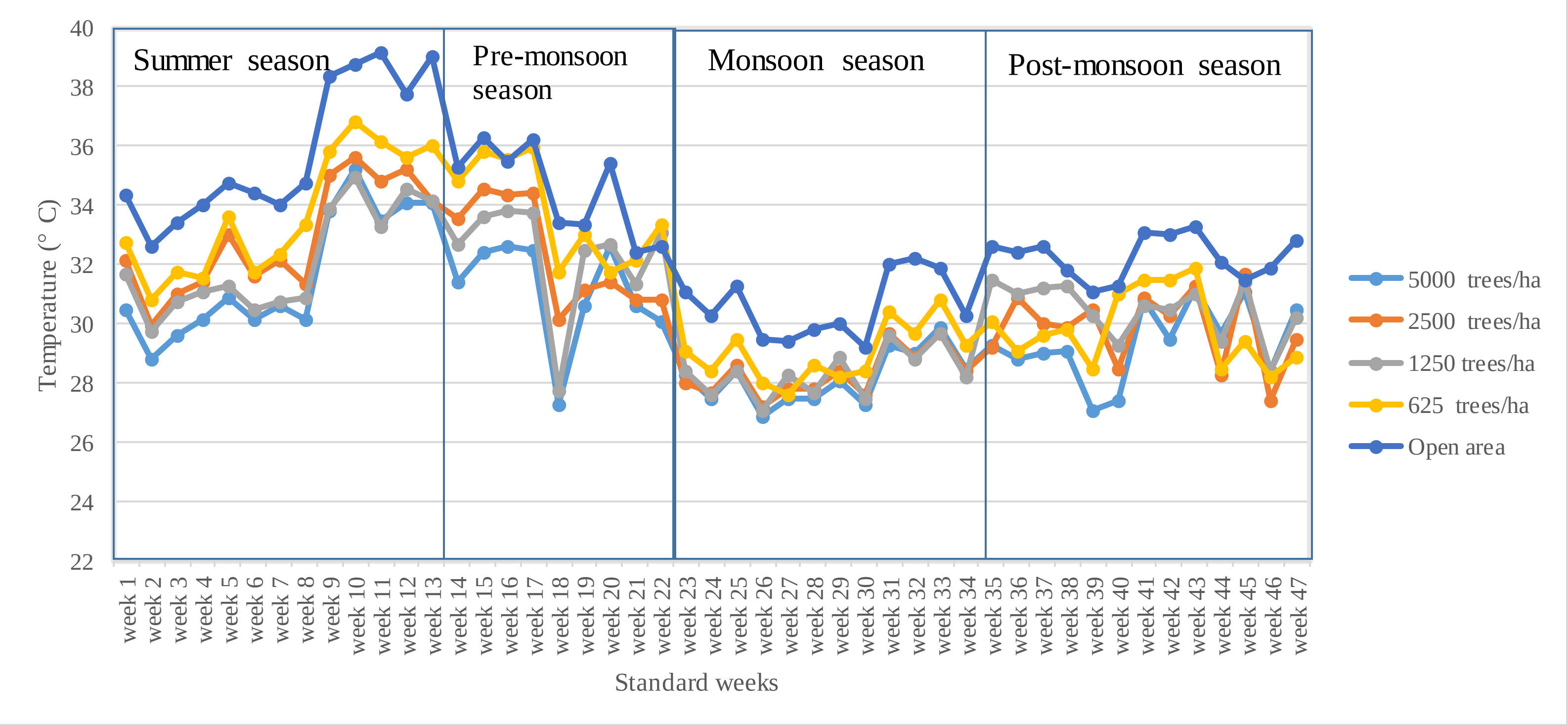


Fig 3. Weekly variation of air temperature at 10 m above the ground level in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

4.1.2. Soil temperature

The results of variations in soil temperature (ST) values in different seasons as influenced by planting density and pruning is presented in Table 3 and Fig. 4-6. It was observed that the ST values differed significantly in the open when compared to the plantation irrespective of seasons. Significant variation in ST values has been observed among the various planting densities in all seasons except the monsoon season.

The vertical distribution of ST showed a constant decline with increasing depth for all planting densities irrespective of seasons. In general, the higher ST was recorded during the summer season followed by the pre-monsoon. The lowest ST was recorded during the monsoon season and post-monsoon season. Pruning had no significant effect on ST in all seasons except the post-monsoon season.

The higher ST values were observed during the summer season as compared to that of other seasons. At 5 and 10 cm depth, the higher ST (32.10 ° C and 30.95° C at 5 and 10 cm depth respectively) was recorded at the low planting density (625 trees/ha). It was significantly different between the planting densities except a density of 1250 trees/ha. The lower ST (28.77 ° C and 28.08° C at 5 and 10 cm depth) was recorded at the high planting density (5000 trees/ha) which significantly varied between all planting densities but was on par with planting density of 2500 trees/ha. At 20 cm depth, the higher ST (30.65° C) recorded at a density of 625 trees/ha was significantly different from all planting densities. The lower ST (28.17° C) was found at 5000 trees/ha was on par with the density of 2500 trees/ha. The soil temperature values from the high planting density to the low planting density ranged from 28.77 ° C to 32.10 ° C at 5 cm depth, 28.08 ° C to 30.95 ° C at 10 cm depth and 27.80 ° C to 31.65 0 C at 20 cm depth respectively. When compared to that of the open area (control), the percentage decrease in the ST values for 5 cm, 10 cm, and 20 cm depths was 16 %, 15 % and 14 % under the closer spacing and 6 % for all the depths under the wider spacing respectively. Pruning had no significant effect on ST. Pruning and planting density interactions were non-significant.

During the pre-monsoon season, the ST for *Acacia mangium* stand was significantly different from the open area and differ between the planting densities. The ST was found to be decreasing with an increase in planting density. Higher ST value was noticed at the low planting density whereas a lower ST value was noticed at the high planting density irrespective of soil depths. The ST values from the high planting density to the low planting density ranged from 29.32 ° C to 31.24 ° C at 5 cm, 27.16 ° C to 30.94 ° C at 10 cm and 27.03 ° C to 30.47 ° C at 20 cm depth. When compared to that of the open area (control), the percentage decrease in ST values for 5 cm, 10 cm and 20 cm depth was 12% , 15 % and 15 % under the closer spacing whereas 6 % , 4 % and 4 % under the wider spacing respectively. No significant differences were found for pruning treatments. Spacing and pruning interaction effects were non-significant.

During the monsoon season, the ST measured at different depths in various planting densities of the *A. mangium* stand was significantly lower from the open area. However, the ST values were not statistically different between the planting densities. The ST values from the high planting density to the low planting density varied from 25.29 ° C to 25.47 ° C at 5 cm depth, 24.56 ° C to 24.85 ° C at 10 cm depth and 24.03° C to 24.25 0 C at 20 cm depth. The open area showed the higher ST throughout the season. When compared to that of the open area (control), the percentage decrease in ST values for 5 cm, 10 cm and 20 cm depth was 7 % , 5 % and 3 % under the closer spacing whereas 4 %, 3 % and 2 % under the wider spacing respectively. The ST was not significantly affected by pruning and spacing and pruning interactions.

During the post-monsoon season, the ST value followed variation similar to that of previous seasons. The ST varied significantly between the open area as well as among the various planting densities of *Acacia mangium* stand. The higher value recorded at the density of 625 trees /ha was significantly different between all planting densities except a density of 1250 trees /ha at different depths. The lower ST found at 5000 trees /ha which was statistically similar with the planting density of 2500 trees /ha.

The ST values from the high planting density to the low planting density varied from 26.73 ° C to 28.72 ° C at 5 cm , 26.07 ° C to 26.73 ° C at 10 cm and 25.39° C to 26.66 ° C at 20 cm depth. When compared to that of the open area (control), the percentage decrease in the ST values for 5 cm, 10 cm and 20 cm depth was 11 % , 10 % and 10 % under the closer spacing whereas 4 %, 8 % and 6 % under the wider spacing respectively. The pruned stands had significantly higher ST at 5 cm depth (27.97 ° C) as compared to that of the unpruned stands (27.40 ° C). However, pruning had no significant effect on the ST at 10 cm and 20 cm depth.

4.1.3. Canopy-air temperature difference (CATD)

The canopy-air temperature difference (CATD) recorded during the summer, pre-monsoon, monsoon and post-monsoon seasons are presented in Table 4 and Fig. 7. Results reveal statistically significant differences between spacing treatments for the summer and pre-monsoon seasons and no differences for the monsoon and post-monsoon seasons. Pruning had no significant effect on CATD during the study period.

During the summer season, the CATD were higher as compared to that of the other seasons for all treatments. The CATD values were increased significantly with an increasing planting density. The CATD (+1.49 ° C) found at a density of 5000 trees/ha did not vary between the planting densities except a density of 625 trees/ha (+2.10 ° C). Pruning had no significant effect on CATD. No significant differences were observed for planting density and pruning interactions.

During the pre-monsoon season, the higher CATD associated with high planting density (+0.92 ° C) was significantly different with all planting densities except a density of 2500 trees/ha. The lower CATD associated with low planting density (+0.16° C) did not differ between the planting densities of 2500 trees/ha and1250 trees/ha. The CATD did not show significant differences for pruning treatments and planting density vs. pruning interactions

Table 3. Soil temperature at various depths in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

	Soil temperature (° C)											
Planting density (trees ha^{-1})	Summer			Pre-monsoon			Monsoon			Post-monsoon		
	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm	5 cm	10 cm	20 cm
5000	28.77^{c}	28.08^{c}	27.80^{d}	29.32^{d}	27.16^{e}	27.03^{d}	25.29^{b}	24.56^{b}	24.03^{b}	26.73^{c}	26.07^{d}	25.39^{c}
2500	29.09^{c}	28.38^{c}	28.01^{d}	28.17^{e}	28.11^{d}	27.53^{d}	25.37^{b}	24.57^{b}	24.10^{b}	26.93^{c}	26.30^{d}	25.60^{c}
1250	31.37^{b}	30.75^{b}	30.17^{c}	30.42^{c}	29.77^{c}	29.36^{c}	25.39^{b}	24.68^{b}	24.10^{b}	28.37^{b}	28.16^{b}	26.43^{b}
625	32.10^{b}	30.95^{b}	30.65^{b}	31.24^{b}	30.94^{b}	30.47^{b}	25.47^{b}	24.85^{b}	24.25^{b}	28.72^{b}	27.73^{c}	26.66^{b}
Open	34.25^{a}	33.14^{a}	32.61^{a}	33.44^{a}	32.30^{a}	31.83^{a}	28.35^{a}	28.08^{a}	27.91^{a}	30.12^{a}	29.18^{a}	28.44^{a}
Pruning												
Unpruned	30.33	29.51	29.41	29.76	28.98	28.55	25.22	24.57	24.03	27.40^{b}	26.73	25.98
50% pruning	30.34	29.56	29.41	29.82	29.03	28.65	25.52	24.77	24.22	27.97^{a}	26.90	26.23
Spacing vs. pruning	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Values with same superscript do not differ significantly
ns-not significant

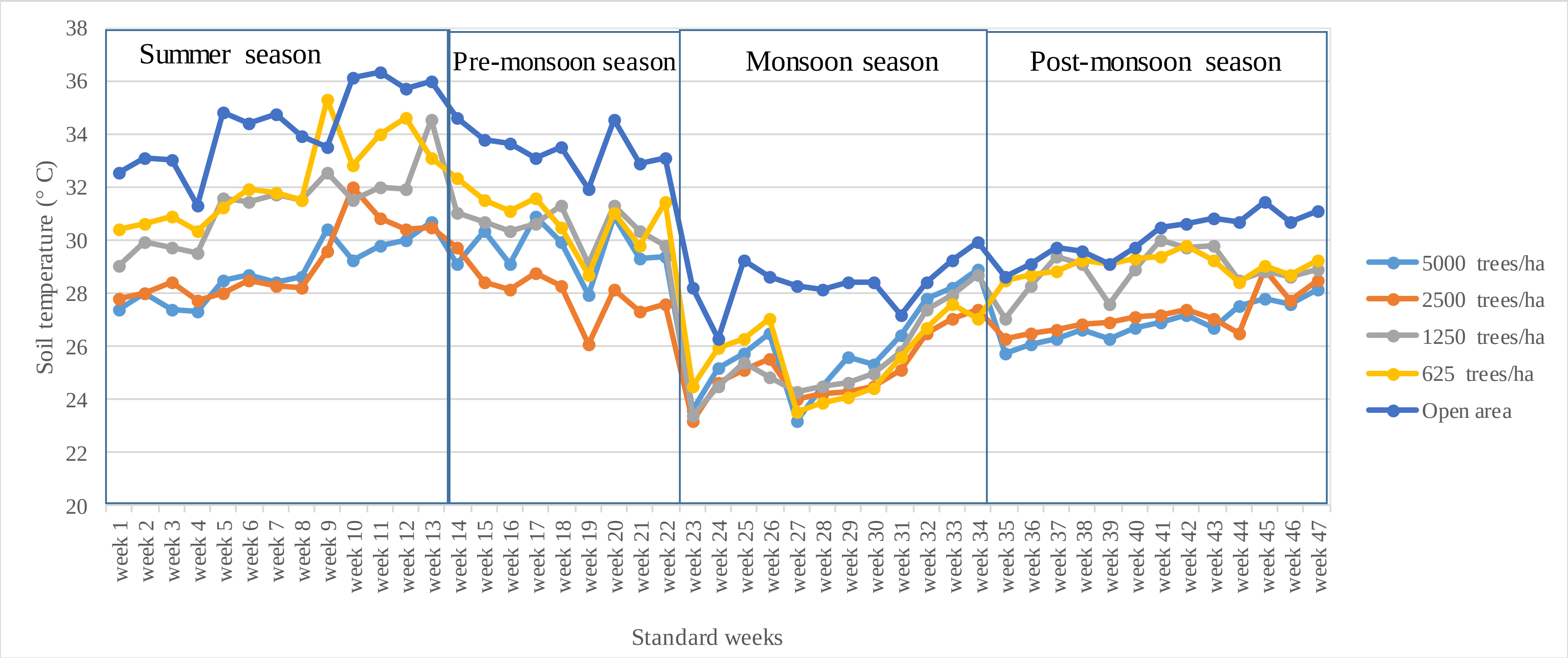


Fig 4. Weekly variation of soil temperature at 5 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

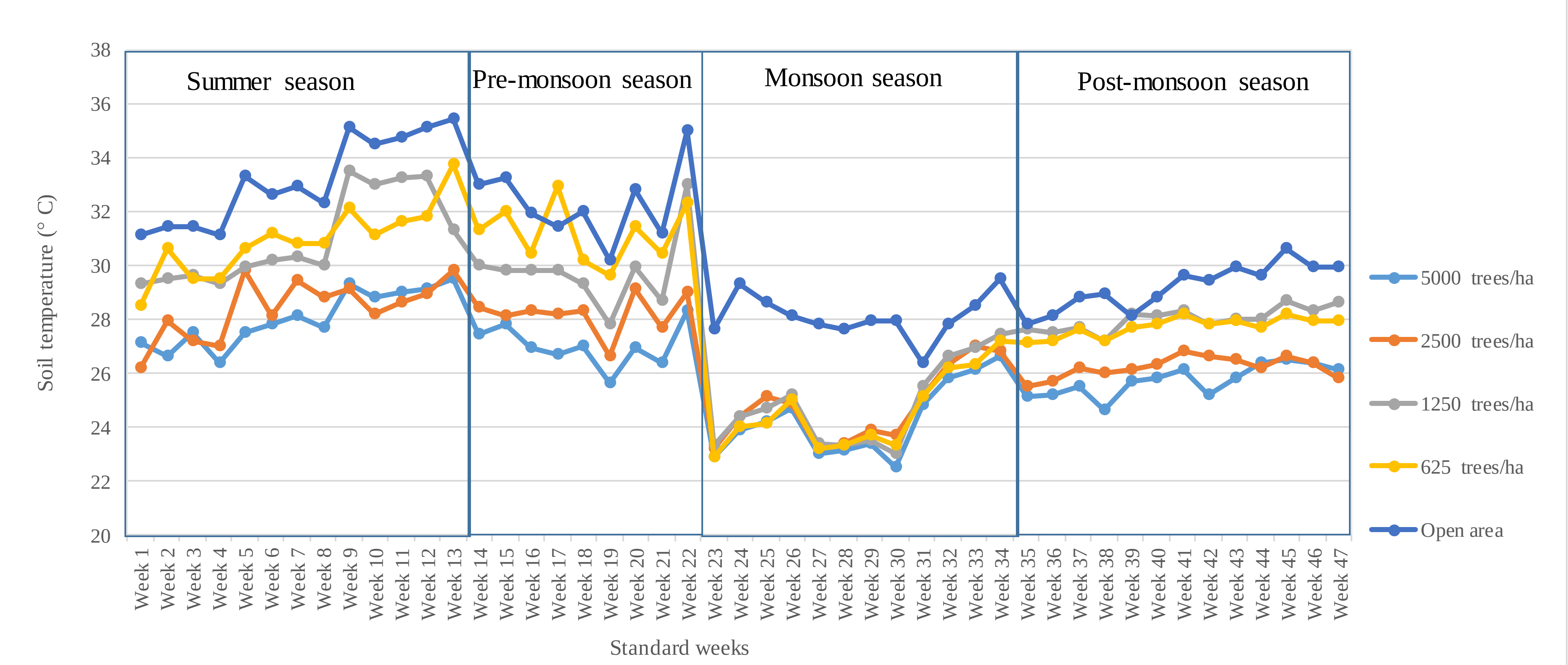


Fig 5. Weekly variation of soil temperature at 10 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

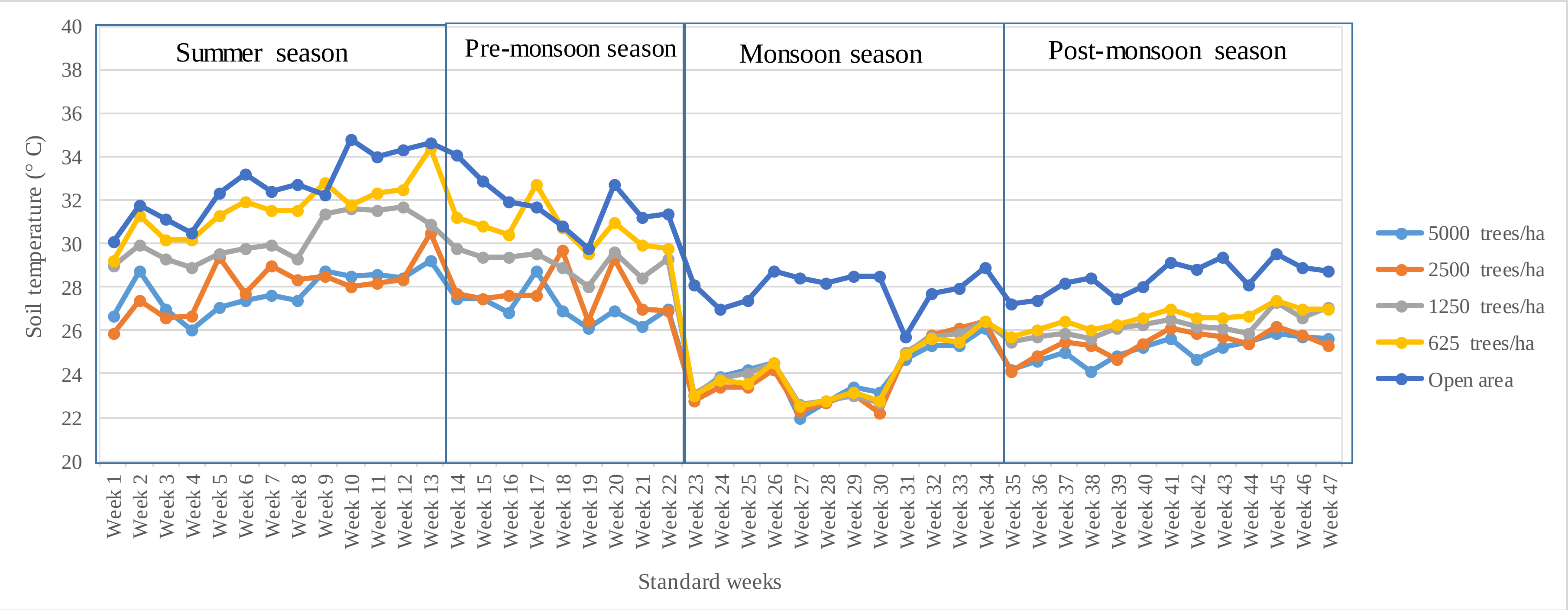


Fig 6. Weekly variation of soil temperature at 20 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

During the monsoon season, the CATD was lesser as compared to that of other seasons for all treatments. No significant differences was observed between the planting densities. The values of CATD from the high planting density to low planting density ranged from -2.69 ° C to -2.81 ° C. The CATD was not affected by pruning treatments. No significant differences were observed for the planting density and pruning interactions.

During the post-monsoon season, the CATD values did not vary significantly between the different planting densities of *Acacia mangium* stand. However, the higher CATD value was associated with high planting density (-0.35 ° C) and the lower CATD value was associated with low planting density (-1.07 ° C). The values of CATD from the high planting density to the low planting density ranged from -0.35 ° C to -1.07 ° C. The CATD was not significantly affected by pruning. No significant differences were observed for planting density and pruning interactions.

Table 4. Canopy-air temperature difference (CATD) in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala

	CATD (° C)			
Planting density (trees ha^{-1})	Summer	Pre-monsoon	Monsoon	Post monsoon
5000	2.10^{a}	0.92^{a}	-2.69	-0.35
2500	2.49^{ab}	0.49^{ab}	-2.64	-0.54
1250	1.80^{ab}	0.16^{b}	-2.63	-0.91
625	1.49^{b}	0.27^{b}	-2.81	-1.07
Pruning				
No pruning	2.04	0.49	-2.59	-0.54
50% pruning	1.90	0.42	-2.80	-0.90
Spacing and Pruning	ns	ns	ns	ns

Values with same superscript do not differ significantl

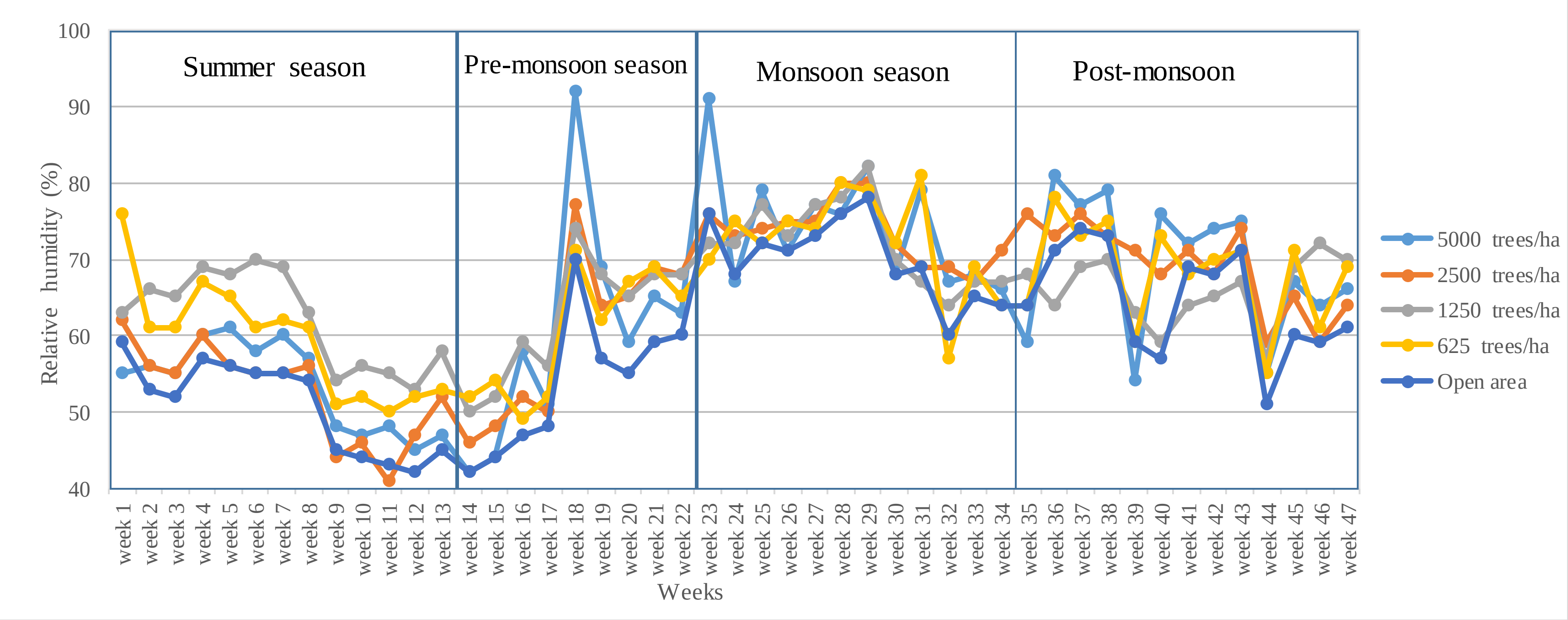


Fig 7. Weekly variation of canopy-air temperature difference (CATD) in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

4.2. MOISTURE ENVIRONMENT

4.2.1. Relative humidity (RH)

Relative humidity (RH) during summer, pre-monsoon, monsoon and post-monsoon seasons are presented in Table 5 and Fig. 8-9. Significant differences in RH values were observed only for the summer season with respect to varying planting densities. The maximum RH was recorded during the monsoon season while minimum RH value was recorded during the summer season. The RH did not show significant differences for pruning treatments during the study period.

During the summer season, the RH values were generally lower for all treatments. The higher RH value was associated with the high planting density (61.42 % and 60.76 % for 5 m and 10 m height respectively) significantly differed from RH recorded at the low planting density (55.92 % and 55.30 % for 5 m and 10 m height respectively). The open area (control) showed lower RH value (50.76%) throughout the season. When compared to that of open area (control), the percentage increase in RH value at the height of 5 and 10 m above ground level was 21 % and 19 % under the closer spacing and 10 % and 9% under the wider spacing. Pruning had no significant effect on RH. The RH values from the unpruned stands and the pruned stands varied from 60.26 % to 57.78 % for 5 m and 59.19 % to 56.98 % for 10 m height above the ground level respectively. No significant differences were observed for spacing and pruning interactions.

During the pre-monsoon season, the RH values were significantly different from the open area but did not vary between the different planting densities. The RH values from the high planting density to the low planting density ranged between 65.60 % to 62.72 % for 5 m and 63.66 % to 60.72 % for 10 m height above the ground level respectively. The open area (control) showed lower RH value (53.5%) throughout the season. When compared to that of the open area (control), the percentage increase in RH value at the height of 5 m and 10 m above ground level was 22 % and 18 % under the closer spacing whereas 11 % and 13% under the wider spacing respectively.

RH was not significantly affected by pruning treatments. The values of RH in the unpruned stand and pruned stand varied between 65.16 % to 62.63% for 5 m and 63.16 % to 60.62 % for 10 m height above the ground level respectively. No significant spacing and pruning interactions were observed.

The RH patterns during the monsoon season followed a trend similar to the pre-monsoon season and generally showed the higher values as compared to that of previous seasons. The RH did not show any significant differences with respect to planting densities of the *Acacia mangium* stand. The values of RH of the high planting density and low planting density varied from 76.71 % to 74.37 % for 5 m and 75.16 % to 72.25% for 10 m height above the ground level respectively. The open area showed a lower RH value (70%) throughout the season. When compared to that of the open area (control), the percentage increase in RH value for 5 and 10 m above the ground level was 9 % and 7 % under the closer spacing whereas 6 % and 3 % under the wider spacing respectively. The RH did not show any significant differences with respect to pruning treatments. The RH values from the unpruned stands to the pruned stands varied between 75.22 % to 75.06 % for 5 m and 73.17 % to 73.29 % for 10 m height above the ground level respectively. No significant differences observed for spacing and pruning interactions.

During the post-monsoon season, it was found that RH values recorded in the *Acacia mangium* stand were significantly different from the open area but did not differ among the planting densities. The RH values from the low planting density to the high planting density varied from 70.50 % to 71.19 % for 5 m and 69.19 % to 68.50 % for 10 m above the ground level respectively. The open area had the lower RH value (64.38%) throughout the season. When compared to that of the open area (control), the percentage increase in the RH value at the height of 5 m and 10 m above the ground level was 10 % and 7 % under closer spacing whereas 10 % and 5 % under wider spacing respectively. Pruning had no significant effect on relative humidity.

Despite the statistical insignificance, the unpruned stand had higher RH value (71.32 % and 69.32 % for 5 m and 10 m above the ground level respectively) compared to that of the pruned stand (70.07 % and 68.07 % for 5 m and 10 m above the ground level respectively). No statistically significant differences observed for spacing and pruning interactions.

Table 5. Relative humidity at the height of 5 and 10 m above the ground level in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

	Relative humidity (%)							
Planting density (trees/ha)	Summer		Pre-monsoon		Monsoon		Post-monsoon	
	5m	10m	5m	10m	5m	10m	5m	10m
5000	61.42^{a}	60.76^{a}	65.66^{a}	63.66^{a}	76.47^{a}	75.16^{a}	71.19^{a}	69.19^{a}
2500	60.34^{ab}	59.26^{ab}	64.05^{a}	62.05^{a}	75.16^{a}	73.54^{a}	71.00^{a}	69^{a}
1250	58.42^{ab}	57.0^{ab}	63.16^{a}	61.16^{a}	74.62^{a}	72.37^{a}	70.11^{a}	68.11^{a}
625	55.92^{b}	55.30^{b}	62.72^{a}	60.72^{a}	74.37^{a}	72.25^{a}	70.50^{a}	68.50^{a}
Open	50.76^{c}	50.76^{c}	53.55^{b}	53.55^{b}	70.0^{b}	70.00^{b}	64.38^{b}	64.38^{b}
Pruning								
Unpruned	60.26	59.19	65.16	63.16	75.23	73.17	71.32	69.32
50% pruning	57.78	56.98	62.63	60.63	75.06	73.29	70.07	68.07
Spacing and Pruning	ns	ns	ns	ns	ns	ns	ns	ns

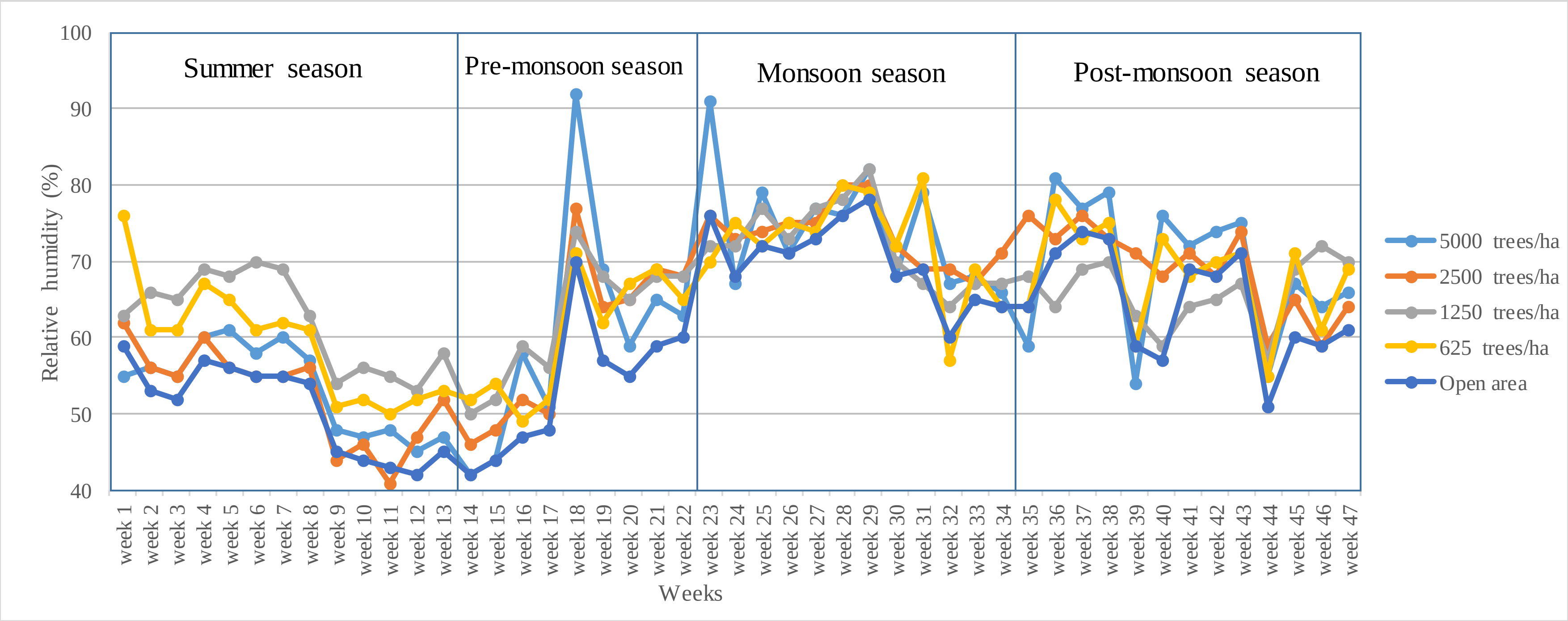


Fig 8. Weekly variation of relative humidity at the height of 5m above the ground level in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

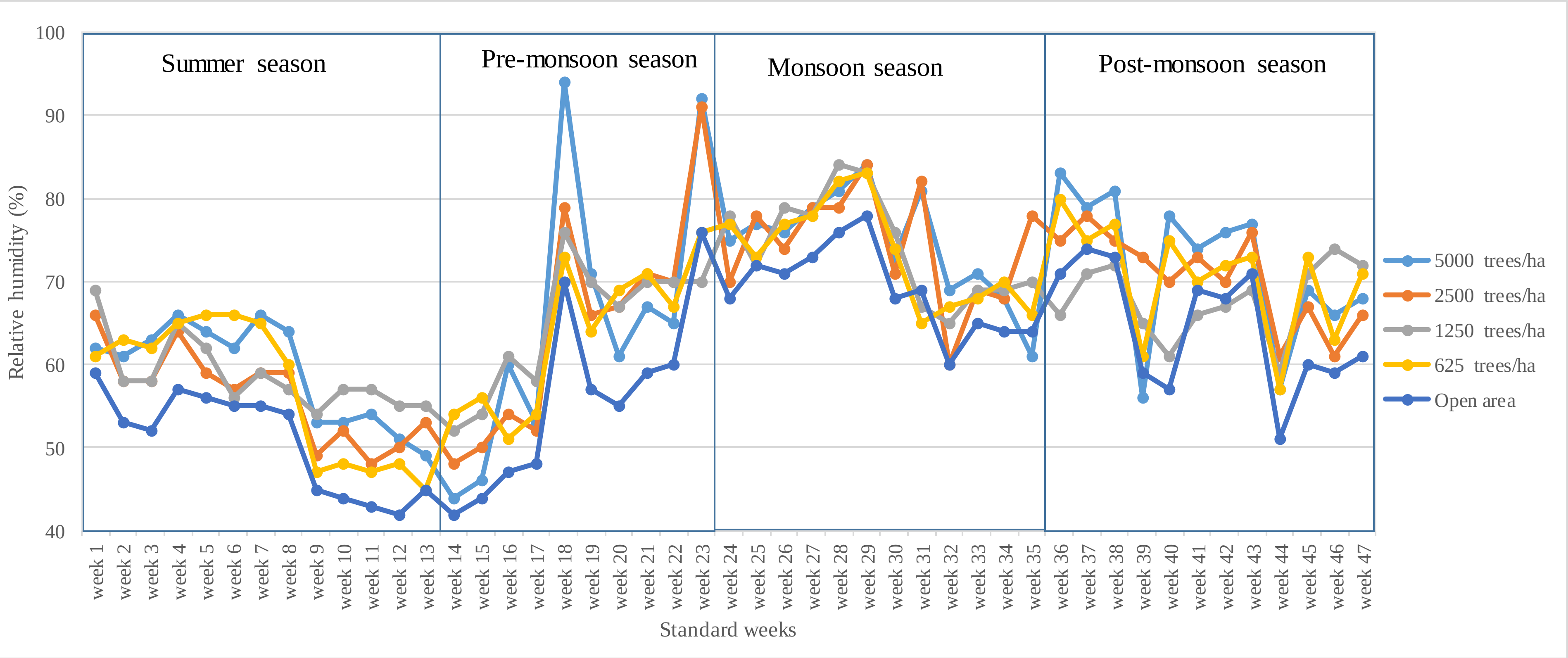


Fig 9. Weekly variation of relative humidity at the height of 10 m above the ground level in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

4.2.2. Soil moisture content (SMC)

The estimation of SMC during the summer, pre-monsoon, monsoon and post-monsoon seasons are presented in Table 6 and Fig. 10-13. Significant variation in the SMC values was observed between the different planting densities in all seasons except monsoon season. The higher soil moisture retention was observed during the monsoon season followed by the post-monsoon season. The lower soil moisture retention was observed during the summer and pre-monsoon season.

During the summer season, the SMC showed lower values as compared to that of other seasons for all treatments. The SMC recorded in *Acacia mangium* stand with different planting densities was significantly higher than that of the open area at both surface and subsurface level. At 5 cm depth, SMC value at the high planting density was significantly higher (13.80 %) than that of the low planting density. Soil moisture content between the planting densities of 5000 trees/ha, 2500 trees /ha and 1250 trees /ha were on par. Similarly, at 10 cm depth, the higher SMC was found at the high planting density (14.79 %) and lower SMC (12.82 %) was found at the low planting density. Statistically, similar values were found between the planting densities of 2500 trees/ha and 1250 trees/ha. At sub-surface level, the SMC showed significant differences from the open area as well as between the planting densities. The higher SMC value was found at the lower planting density (16.35 % and 17.94 % at 20 cm and 30 cm depth respectively). This considerably decreases with an increase in planting density and recorded the lower SMC at the high planting density (13.45 % and 13.89 % at 20 cm and 30 cm depth respectively). When compared to that of the open area (control), the percentage increase in the SMC value for 5 cm, 10 cm , 20 cm and 30 cm depth was 74 % , 56 % , 28% and 16% under the closer spacing whereas 36 %, 35 %, 56% and 50 % under the wider spacing respectively. Pruning had no significant effect on SMC.

The SMC values from the pruned stand to the unpruned stands varied between 12.21 % to 12.90 % for 5 cm depth and 15.71 % to 14.01% for 10 cm depth respectively while at subsurface level, the SMC values showed reverse trend as it varied between 15.16 % to 14.30 % for 20 cm depth and 15.78 % to 15.29% for 30 cm depth respectively. A significant difference on SMC values at 5 cm, 10 cm, and 20 cm depths was observed for pruning and spacing interactions while no significance was observed at 30 cm depth.

During the pre-monsoon season, at surface level, the higher SMC value was associated with a density of 5000 trees/ha (16.09 % and 16.80 % at 5 cm and10 cm depth respectively). There was a significant variation between all planting densities. The lower SMC was noticed at a density of 625 trees/ha (11.69 % and 13.53 % at 5 cm and 10 cm depth respectively). However, the SMC observed between the planting densities of 2500 trees/ha and 1250 trees/ha was statistically similar to each other. While at sub-surface, the higher SMC value was noticed at the low planting density (19.04 % and 20.33 % at 20 cm and 30 cm depth respectively). SMC generally decreased with increase in stand density and recorded lowest SMC value at high planting density (14.74 % and 16.86 % at 20 cm and 30 cm depth respectively). However, no difference between planting densities of 5000 trees/ha and 2500 trees/ha. The open area recorded the lowest SMC throughout the season at both surface and sub-surface level. When compared to that of the open area (control), the percentage increase in SMC value for 5 cm, 10 cm, 20 cm and 30 cm depth was 70 % , 61 % , 24 % and 27 % under the closer spacing whereas 36 %, 30 %, 60 % and 53 % under the wider spacing respectively. The SMC values did not show any significant variation with respect to pruning treatments. The values of SMC from the pruned stands to the unpruned stands varied between 13.52 % to 14.50 % for 5 cm depth and 14.37 % to 15.39 % for 10 cm depth respectively. While at the subsurface, the SMC showed a reverse trend with a variation of 16.86 % to 16.23 % for 20 cm depth and 18.39 % to 18.05 % for 30 cm depth respectively. A significant difference on the SMC at 5 cm, 10 cm and 20 cm depths was observed for pruning and spacing interactions and no significance was observed at 30 cm depth.

The pattern of variation in the SMC during the monsoon season followed a trend similar to that of previous seasons. The SMC were significantly different between the open area and planting densities of *Acacia mangium* plantation for all depths except 5 cm depth. However, the SMC values were not significantly different between the planting densities. The SMC values from the high planting density to the low planting density varied from 24.08 % to 20.86 % for 5 cm depth and 22.94 % to 21.79 % for 10 cm depth respectively. While at the sub-surface level, it followed a reverse trend as it varied between 25.27 % to 24.31 % for 20 cm depth and 26.81 % to 27.14 % for 30 cm depth respectively. When compared to that of the open area (control), the percentage increase in the SMC value for 5 cm, 10 cm , 20 cm and 30 cm depth was 31 % , 12 % , 2 % and 6 % under the closer spacing whereas 13 %, 7 %, 6% and 5% under the wider spacing respectively. Pruning had no significant effect on SMC. The SMC values from the pruned stands to the unpruned stands varied between 21.66 % to 23.31 % for 5 cm depth and 21.97 % to 22.82 % for 10 cm depth respectively while at subsurface, it varied between 25.38 % to 23.94 % for 20 cm depth and 26.94 % to 26.51 % for 30 cm depth respectively. A significant difference on SMC values at 5 cm, 10 cm and 20 cm depths was observed for pruning and spacing interactions while no significance was observed at 30 cm depth.

During the post-monsoon season, the results reveal that the *Acacia mangium* stand with different spacing treatments showed significantly higher SMC values as compared to that of the open area both at the surface and subsurface soils. At surface level, the high planting density had higher SMC value (19.83 % at 5 cm and 19.51 % at 10 cm depth), which was statistically on par with all planting densities except a density of 2500 trees/ha. The lower SMC was recorded at the low planting density (17.46 % at 5 cm depth and 17.61 % at 10 cm depth respectively) which showed statistically similarity with all planting densities except a density of 5000 trees/ha. At 20 cm depth, SMC was higher in the low planting density (22.09 %) and lower SMC was found at the high planting density (19.64 %).

Table 6. Soil moisture content at various depths in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

	Soil moisture content (%)															
Planting density (trees ha^{-1})	Summer				Pre-monsoon				Monsoon				Post-monsoon			
	5 cm	10 cm	20 cm	30 cm	5 cm	10 cm	20 cm	30 cm	5 cm	10 cm	20 cm	30 cm	5 cm	10 cm	20 cm	30 cm
5000	13.80^{a}	14.79^{c}	13.45^{c}	13.89^{c}	16.09^{a}	16.80^{a}	14.74^{c}	16.86^{c}	24.08^{a}	22.94	24.31	27.14	19.83^{a}	19.51^{a}	19.64^{c}	21.92^{b}
2500	13.91^{a}	14.21^{bc}	13.90^{c}	14.16^{c}	14.17^{b}	14.08^{b}	15.46^{c}	17.24^{c}	23.17^{a}	22.67	24.72	26.40	18.67^{ab}	18.95^{ab}	20.13^{c}	22.53^{a}
1250	11.72^{a}	13.62^{ab}	15.22^{b}	16.14^{b}	14.10^{b}	15.14^{b}	16.92^{b}	18.46^{b}	21.93^{a}	22.22	24.29	26.57	18.20^{b}	18.15^{b}	21.18^{b}	23.04^{a}
625	10.79^{b}	12.82^{a}	16.35^{a}	17.94^{a}	11.69^{c}	13.53^{c}	19.04^{a}	20.33^{a}	20.86^{ab}	21.79	25.27	26.81	17.46^{b}	17.61^{b}	22.09^{a}	24.63^{a}
Open	7.93^{c}	9.46^{d}	10.48^{d}	11.91^{d}	9.42^{d}	10.41^{d}	11.91^{d}	13.31^{d}	18.34^{b}	20.38	23.90	25.55	13.91^{c}	14.66^{c}	17.10^{d}	20.31^{c}
Pruning																
Unpruned	12.90	14.01	14.30	15.29	14.50	15.39	16.23	18.05	23.31	22.82	23.94	26.51	19.56^{a}	19.15^{a}	20.23^{b}	22.55
50% pruning	12.21	13.71	15.16	15.78	13.52	14.38	16.86	18.39	21.66	21.97	25.38	26.94	17.76^{b}	17.96^{b}	21.29^{a}	23.51
Spacing vs. pruning	s	s	s	ns	s	s	s	ns	s	s	s	ns	s	s	s	ns

Values with same superscript do not differ significantly
ns-not significant

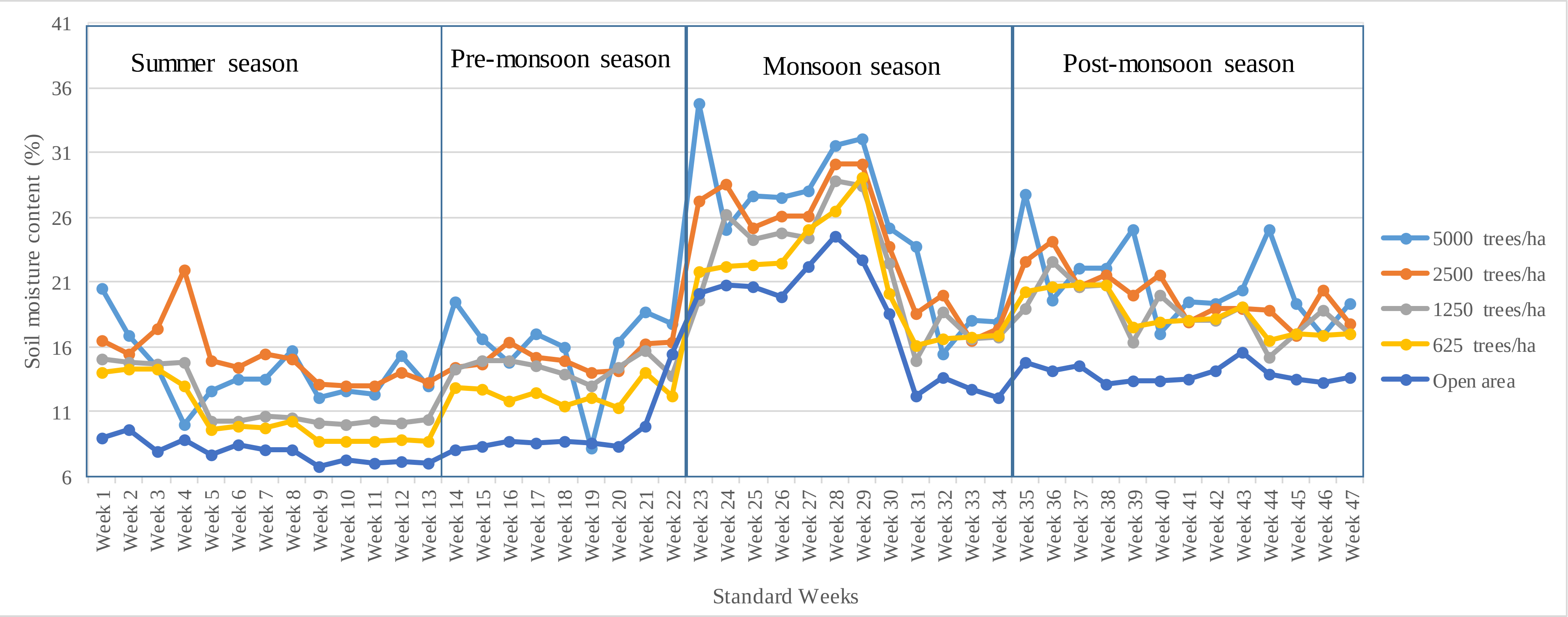


Fig 10. Weekly variation of soil moisture content (SMC) at 5 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

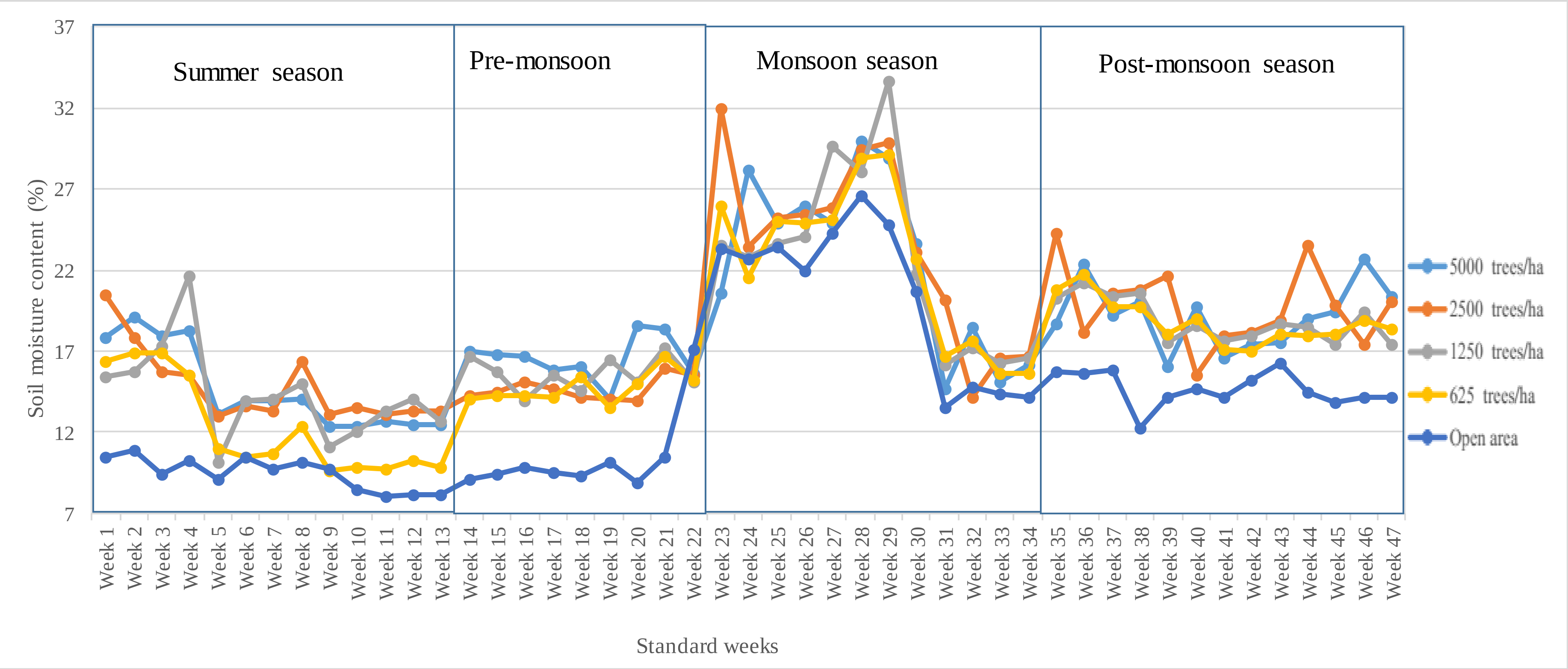


Fig 11. Weekly variation of soil moisture content (SMC) at 10 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

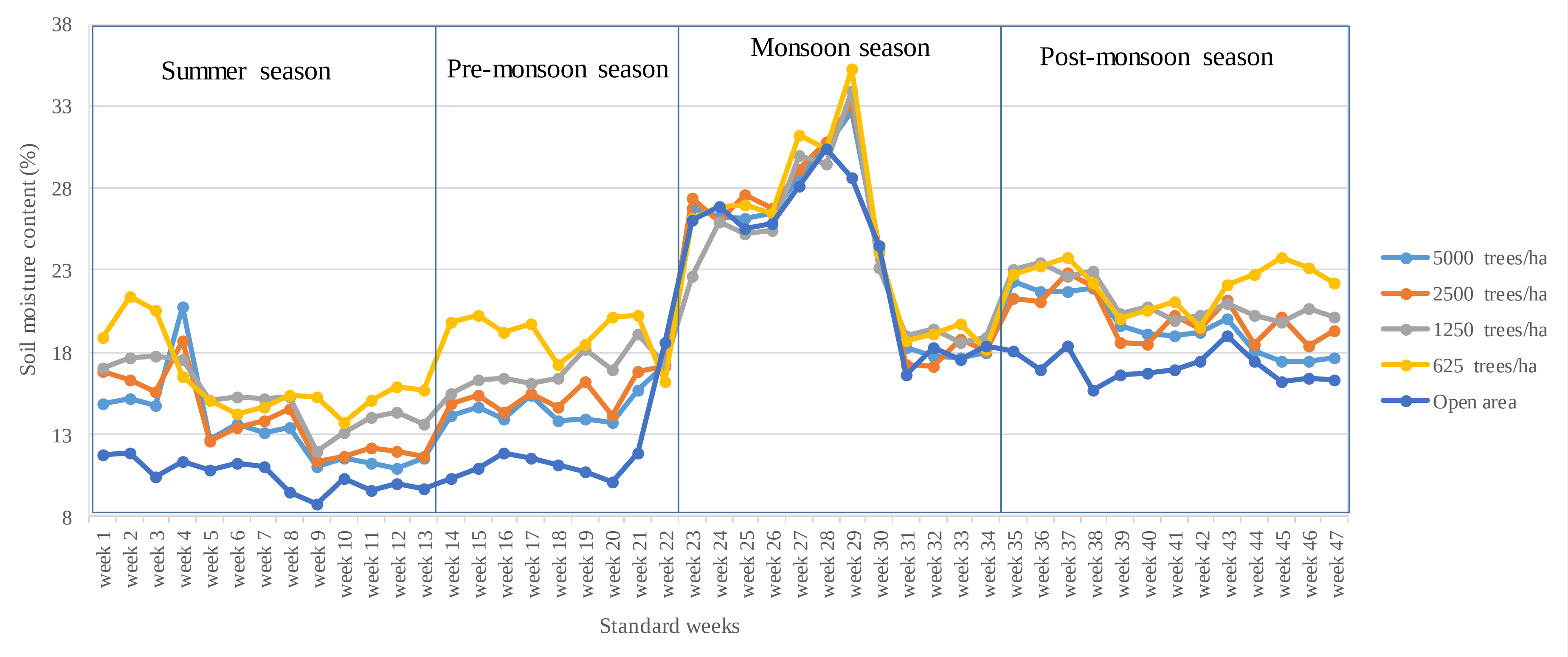


Fig 12. Weekly variation of soil moisture content (SMC) at 20 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

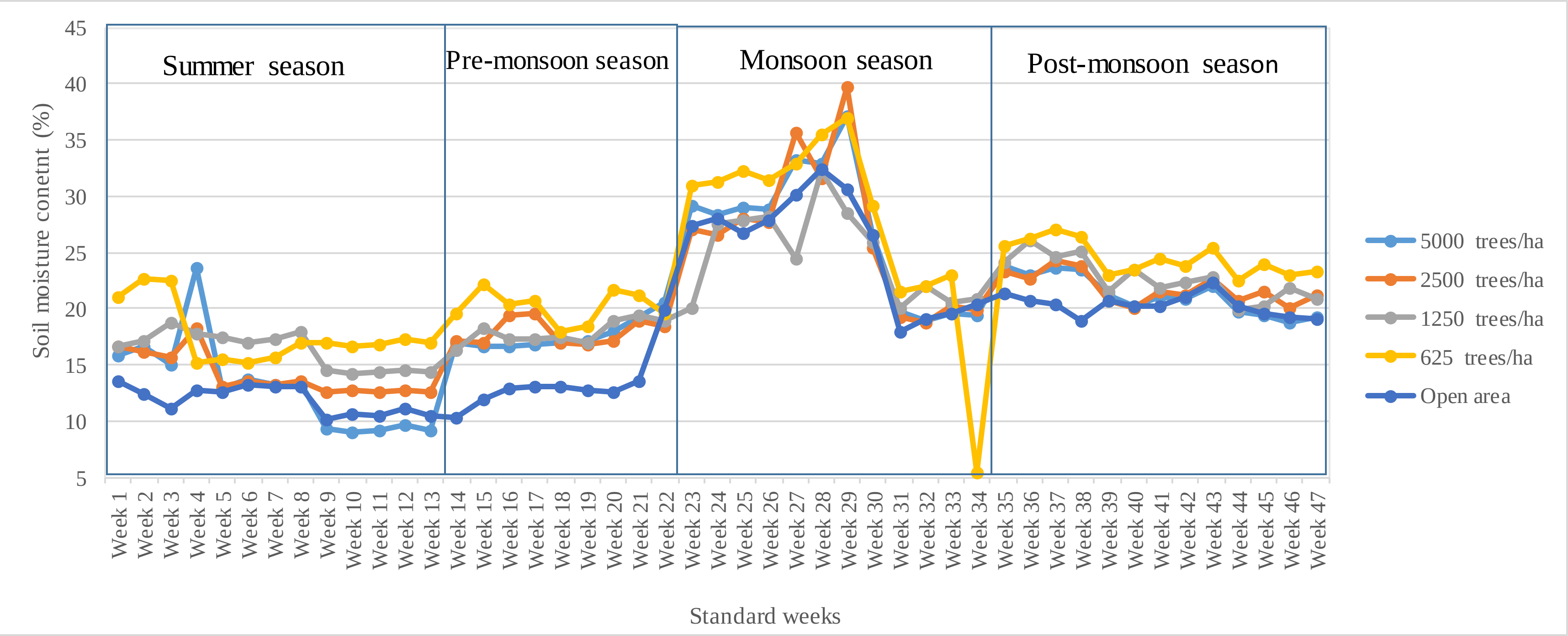


Fig 13. Weekly variation of soil moisture content (SMC) at 30 cm depth in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

At 30 cm depth, the higher SMC observed in the low planting density (24.63%) was significantly different between all planting densities except a density of 5000 trees/ha, which did not differ between them (21.29 %). The control showed the lower SMC throughout the season. When compared to that of the open area (control), the percentage increase in the SMC value for 5 cm, 10 cm, 20 cm and 30 cm depth was 42 % , 33 % , 15 % and 5% under the closer spacing whereas 26 %, 21 % ,30 % and 22 % under the wider spacing respectively. At surface level, the pruned stands had significantly lower SMC (17.76 % and 17.96 % for 5 cm and 10 cm depth respectively) then compared to that of the unpruned stands (19.56 % and 19.15 % for 5 cm and 10 cm respectively) while at the subsurface level, the higher SMC value was associated with the pruned stands (21.29 % and 23.51 % for 20 cm and 30 cm depth respectively) as compared to that of the unpruned stands (20.23 % and 22.55 % for 20 cm and 30 cm depth respectively) but pruning had no significant effect on SMC at 30 cm depth.

4.2.3. Relative water content

The results of estimation of relative water content (RWC) during the summer, pre-monsoon, monsoon and post-monsoon seasons are presented in Table 7 and Fig. 14. On statistical analysis, it was found that RWC was significantly different between the various spacing treatments in different seasons. Generally, RWC values were higher during the monsoon season followed by post-monsoon season and lower values were recorded during the summer and pre-monsoon season.

During the summer season, the RWC was lower when compared to that of the other seasons for all treatments. The higher RWC was observed for the low planting density (72.13%) and the lower RWC value (65.13%) was observed for the high planting density. The RWC values did not statistically differ between the planting densities of 5000 trees/ha and 2500 trees/ha, 2500 trees/ha and 1250 trees/ha and 1250 trees/ha and 625 trees/ha. Pruning, as well as planting density and pruning interactions, had no significant effect on RWC.

During the pre-monsoon season, the RWC was significantly affected by planting densities of the *Acacia mangium* stand. The low planting density had significantly higher RWC value (73.29 %) than that of other planting densities and the lower RWC value was recorded at the high planting density stand (68.56 %). However, the RWC did not vary between the planting densities of 5000 trees/ha and 2500 trees/ha and between planting densities of 1250 trees/ha and 625 trees/ha respectively. The pruned stands had significantly higher RWC (72.71%) as compared to that of the unpruned stands (69.38%). No significant differences were observed for planting density and pruning interactions.

During the monsoon season, the RWC was higher as compared to that of other seasons for all treatments but did not vary between different planting densities of *Acacia mangium* stand. The RWC values from the low planting density to the high planting density varied from 84.22 % to 81.44 %. The RWC did not show any significant differences for pruning treatments and planting density and pruning interactions.

During the post-monsoon season, it was once again found that RWC values significantly varied between the different planting densities. The lower RWC (75.63 %) found at the high planting density was statistically on par with all planting densities except a density of 625 trees/ha. The higher RWC (78.73%) recorded in the low planting density did not differ from other planting densities except a density of 5000 trees/ha. The pruned stands had significantly higher RWC (78.63 %) when compared to that of the unpruned stands (75.75 %). No significant influence were observed for planting density and pruning interactions.

Table 7. Relative Water Content (RWC) in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

Values with same superscript do not differ significantly
ns-not significant

	RWC (%)			
Planting density (trees ha^{-1})	Summer	Pre-monsoon	Monsoon	Post-monsoon
5000	65.13^{c}	68.56^{b}	81.84	75.67^{b}
2500	67.84^{bc}	70.19^{b}	81.86	76.63^{ab}
1250	69.54^{ab}	72.14^{a}	84.00	77.74^{ab}
625	72.31^{a}	73.29^{a}	84.22	78.73^{a}
Pruning				
Unpruned	68.54	69.38^{b}	82.29	75.75^{b}
50% pruning	68.87	72.71^{a}	83.67	78.63^{a}
Spacing vs. pruning	ns	ns	ns	ns

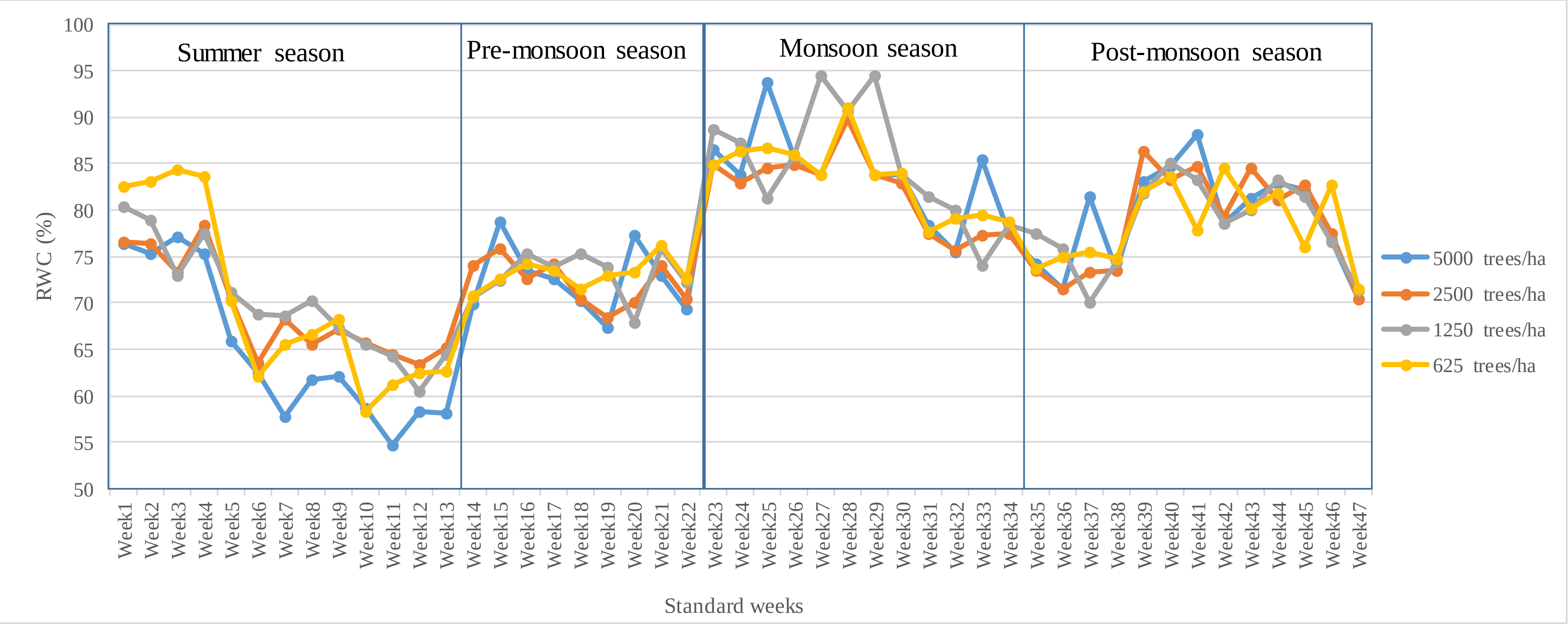


Fig 14. Weekly variation of relative water content (RWC) in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

4.2.4. Evapotranspiration

The evapotranspiration (ET) estimates during the summer, pre-monsoon, monsoon and post-monsoon seasons are given in Table 8 and Fig. 15. On statistical analysis, it was found that ET values for the *Acacia mangium* stand were statistically significant between the various spacing treatments for all seasons except monsoon season.

During the summer season, the ET showed the higher values as compared to that of the other seasons for all treatments. The lower ET associated with the high planting density (5.50 mm) was significantly different between all planting densities except a density of 2500 tree/ha. The lower planting density recorded the higher ET (6.92 mm), which was significantly different from other planting densities except a density of 1250 trees/ha. Pruning had no significant effect on ET. No significant differences were observed for planting density and pruning interactions.

During the pre-monsoon season, the lower ET value (4.92 mm) was recorded for the high planting density was statistically similar between all planting densities except a density of 625 trees/ha (6.18 mm). No significant differences were observed with respect to pruning treatments and planting density vs. pruning interactions.

During the monsoon season, the ET showed lesser values as compared to that of other seasons for all treatments. It was found that ET did not statically differ among the various planting densities of *Acacia mangium* stand. The values of ET from the low planting density to the high planting density varied from 3.35 mm to 2.74 mm. The ET did not show any significant differences for pruning treatments and planting density vs. pruning interactions.

During the post-monsoon season, it was found that the ET values were varied significantly between the different planting densities of *Acacia mangium* plantation.

The low planting density had significantly higher ET (3.87 mm) as compared to that of other planting densities and the lower ET value was recorded at density of 2500 trees/ha (3.26 mm).

The ET recorded between the planting densities of 5000 trees/ha and 2500 trees/ha and also between 1250 trees/ha and 625 trees/ha were non-significant. The unpruned stand had significantly higher ET (3.81 mm) when compared to that of the pruned stand (3.54 mm). No significant differences were observed for planting density and pruning interactions.

Table 8. Evapotranspiration (ET) in *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

	ET (mm)			
Planting density (trees ha^{-1})	Summer	Pre-monsoon	Monsoon	Post-monsoon
5000	5.50^{c}	4.92^{b}	2.74	3.50^{b}
2500	6.04^{bc}	5.25^{b}	3.15	3.26^{b}
1250	6.47^{ab}	5.66^{ab}	3.19	4.08^{a}
625	6.92^{a}	6.18^{a}	3.35	3.87^{a}
Pruning				
No pruning	6.27	5.61	3.26	3.81^{a}
50% pruning	6.20	5.39	2.95	3.54^{b}
Spacing and Pruning	ns	ns	ns	ns

Values with same superscript do not differ significantly
ns-not significant

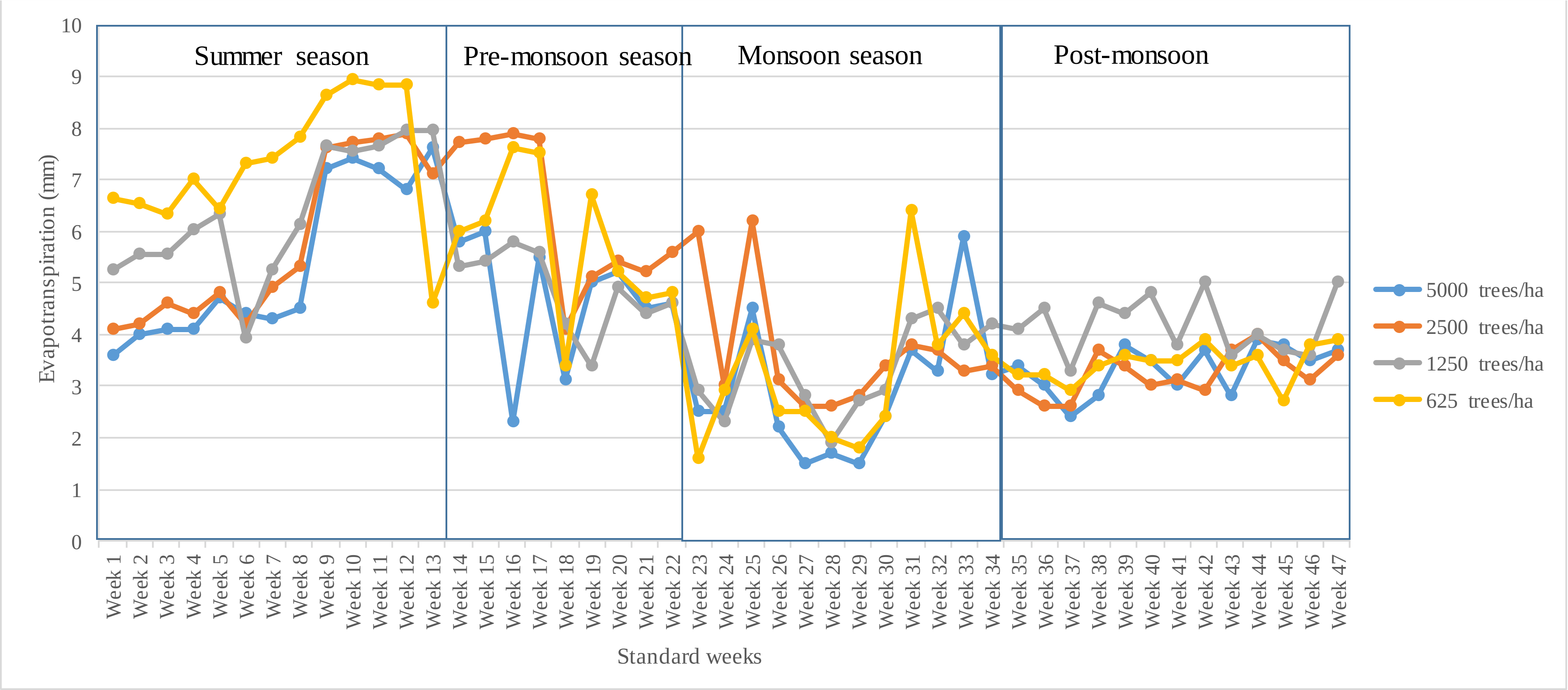


Fig 15. Weekly variation of evapotranspiration (ET) in *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

4.3. THERMAL ENVIIRONMENT

4.3.1. Photosynthetically active radiation (PAR)

The results of PAR during the summer, pre-monsoon, monsoon and post-monsoon seasons are given in Table 9 and Fig. 16-17. The statistical analysis of the given values showed a significant difference between the open area (control) and *Acacia mangium* plantation where spacing treatments were implemented, for all seasons. The higher PAR values were recorded in the open area than the *Acacia mangium* stand irrespective of planting density in all seasons. It was found that the PAR values were statistically differed among the planting densities.

During the summer season, the PAR generally showed higher values for all treatments. The higher PAR found at the low planting density (263 W/m^2 and 276 W/m^2 for 5 m and 10 m height respectively) was on par with all planting densities, except a density of 5000 trees/ha (149 W/m2 and 171 W/m2 for 5 m and 10 m height respectively). The open area (control) had higher PAR value (804 W/m^2) throughout the season. The percentage of PAR transmittance at the height of 5 m and 10 m above the ground level was observed to be both 21 % under the closer spacing and 32 % and 34 % under the wider spacing respectively when compared to that of the open area (control). Pruning had no significant effect on PAR. The PAR values from the pruned stand to the unpruned stand varied between 222 W/m^2 to 191 W/m^2 for 5 m and 239 W/m^2 to 211 W/m^2 for 10 m height above the ground level respectively. No significant differences were observed for pruning and spacing interactions.

During the pre-monsoon season, the PAR followed the trend of the summer season. The higher PAR value was recorded for the low planting density (225 W/m^2 and 242 W/m^2 for 5 m and 10 m height respectively) which did not vary significantly with all other planting densities except a density of 625 trees/ha. The lower PAR value (120 W/m^2 and 135 W/m^2 for 5 m and 10 m height respectively) was recorded at density of 625 trees/ha, which was statistically similar to planting densities of 2500 trees/ha and 1250 trees/ha.

The open area had the higher PAR value (724 W/m^2) throughout the season. When compared to that of the open area (control), the percentage of PAR transmittance at the height of 5 m and 10 m above the ground level was observed to be 16 % and 18 % under the closer spacing and 31 % and 33 % under the wider spacing respectively. Pruning had no significant effect on PAR. However, the pruned stands had higher PAR value (170 W/m^2 and 186 W/m^2 for 5 m and 10 m height respectively) compared to that of the unpruned stand (163 W/m^2 and 180 W/m^2 for 5 m and 10 m height respectively). No significant differences were observed with respect to pruning and spacing interactions.

The PAR during the monsoon season followed a trend similar to previous seasons but showed lesser values as compared to that of previous seasons. The higher PAR value was associated with the low planting density (154 W/m^2 and 174 W/m^2 for 5 m and 10 m height respectively). This was significantly different with all planting densities except a density of 1250 trees/ha. The lower PAR value associated with the high planting density (84 W/m^2 and 99 W/m^2 for 5 m and 10 m height respectively) which was statistically on par with all planting densities except a density of 2500 trees/ha. The open area had the higher PAR value (420 W/m^2). When compared to that of the open area (control), the percentage of PAR transmittance at the height of 5 m and 10 m above the ground level was observed to be 20 % and 23 % under the closer spacing and 36 % and 41 % under the wider spacing respectively. The PAR did not show any significant differences for pruning treatments. The values of PAR from the pruned stand to unpruned stand ranged between 131 W/m^2 to 108 W/m^2 and 147 W/m^2 to 124 W/m^2 for 5 m and 10 m above the ground level respectively. No significant differences were observed for pruning and spacing interactions.

Observations during the post monsoon season revealed that among the planting densities, the higher PAR value was associated with the low planting density (177 W/m^2 and 192 W/m^2 at 5 m and 10 m height respectively) and the lowest PAR value was associated with high planting density (104 W/m^2 and 120 W/m^2 at 5 and 10 m height respectively).

No significant difference were found between the planting densities of 5000 trees/ha and 2500 trees/ha, 2500 trees/ha and 1250 trees/ha and 1250 trees/ha and 625 trees/ha respectively. When compared to that of the open area (control), the percentage of PAR transmittance at the height of 5 m and 10 m above the ground level was observed to be 18 % and 21 % under the closer spacing and 31 % and 34 % under the wider spacing respectively. The PAR was not affected by pruning. The PAR value from the pruned stand to the unpruned stand varied between 147 W/m^2 to 142 W/m^2 for 5 m and 162 W/m^2 to 158 W/m^2 for 10 m above the ground level respectively. No significant differences were observed for pruning and spacing interactions.

Table 9. Photosynthetically active radiation (PAR) at height of 5 and 10 m above the ground level as influenced by planting density and pruning in *Acacia mangium* stand at Thiruvizhamkunnu, Kerala, India

	PAR (W/m^2)							
Planting density (trees/ha)	Summer		Pre-monsoon		Monsoon		Post-monsoon	
	5m	10m	5m	10m	5m	10m	5m	10m
5000	149^{c}	171^{c}	120^{c}	135^{c}	84^{c}	99^{c}	104^{d}	120^{d}
2500	190^{bc}	211^{bc}	137^{bc}	152^{bc}	106^{c}	122^{c}	134^{cd}	150^{cd}
1250	224^{bc}	240^{bc}	184^{bc}	202^{bc}	136^{bc}	151^{bc}	163^{bc}	177^{bc}
625	263^{b}	276^{b}	225^{b}	242^{b}	154^{b}	171^{b}	177^{b}	192^{b}
Open	804^{a}	804^{a}	724^{a}	724^{a}	420^{a}	420^{a}	556^{a}	556^{a}
Pruning								
Unpruned	191	211	163	180	108	124	142	158
50% pruning	222	239	170	186	133	148	147	162
Spacing Pruning	ns	ns	ns	ns	ns	ns	ns	ns

Values with same superscript do not differ significantly
ns-not significant

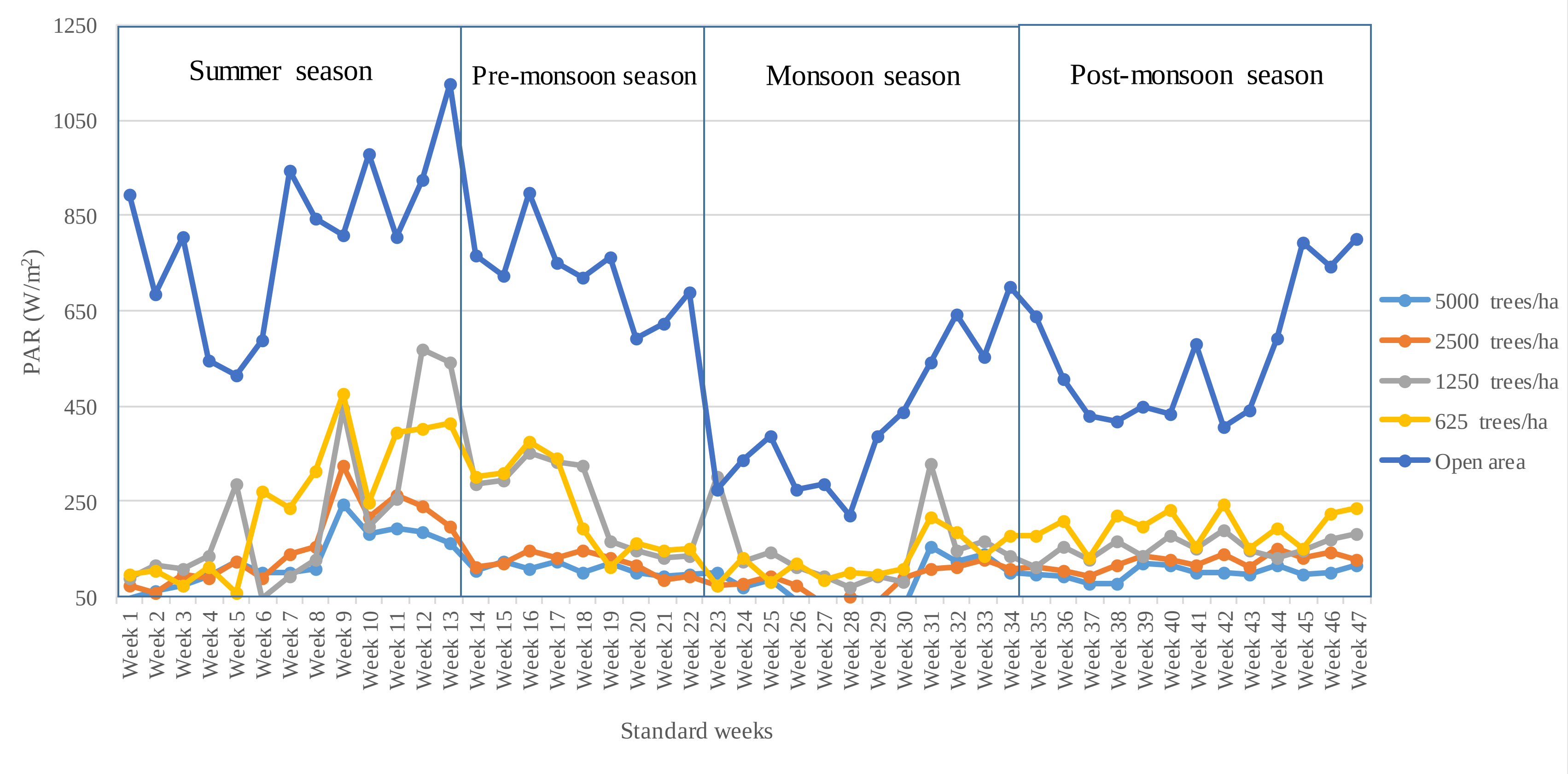


Fig 16. Weekly variation of PAR at the height of 5 m above the ground level *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

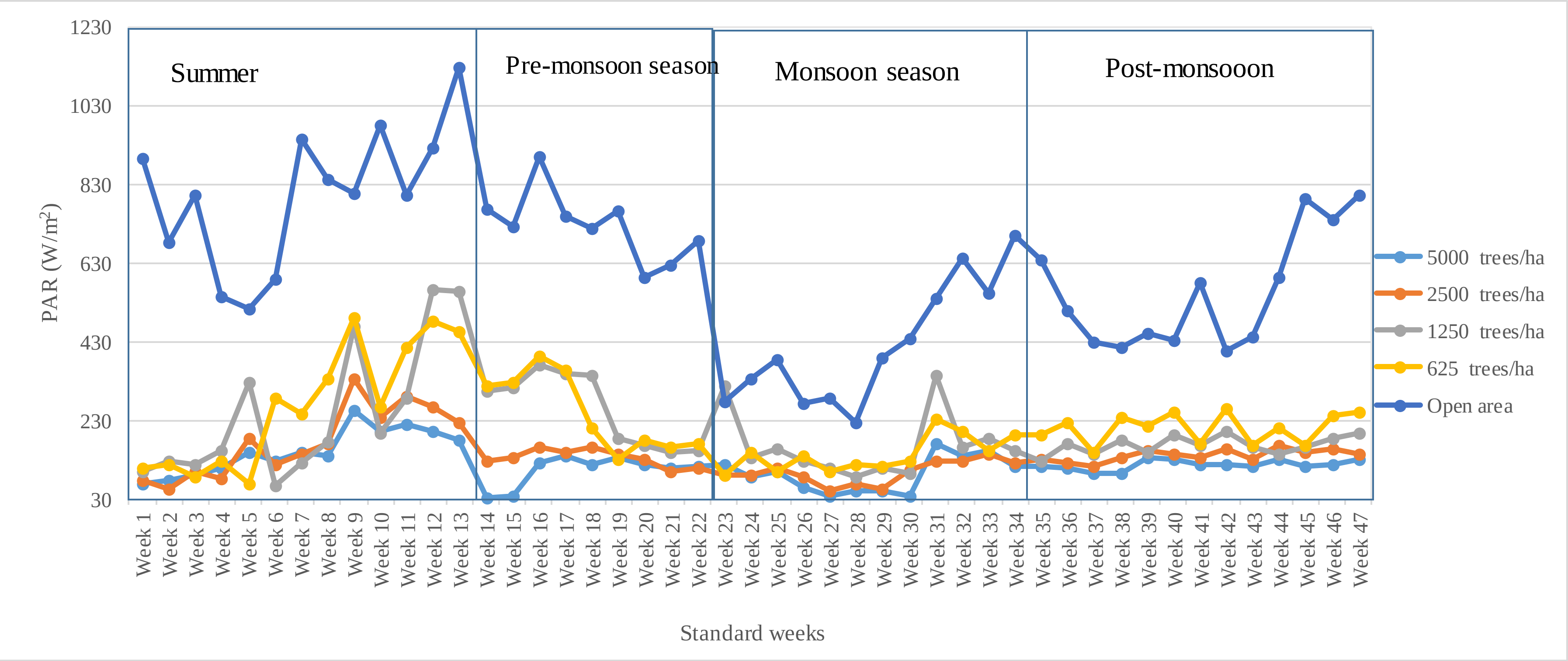


Fig 17. Weekly variation of PAR at the height of 10 m above the ground level *Acacia mangium* stand as influenced by planting density at Thiruvizhamkunnu, Kerala, India

4.3.2. Diurnal variation in photosynthetically active radiation (PAR)

Photosynthetically active radiation (PAR) availability in a fifteen year old *Acacia mangium* stand managed at various planting densities and pruning levels were monitored. The observations of PAR corresponding to the understorey and above the canopy recorded on an hourly basis under various planting densities and pruning levels in *A.mangium stand* from 10-01-2015 to 20-1-2015 are given in Table 10 and Fig. 18(a & b).

Considerable variation in the PAR interception was observed for different planting densities. The unpruned stands of the high planting density (5000 trees ha-1) showed the lower PAR transmittance during the early three hours then it followed the increasing trend from 12.00 noon to 2.00 pm. The highest PAR transmittance was about 24% which was observed at 1.00 pm. For the pruned stands, the PAR transmittance increased from 9 am to 1 pm with the higher value (29%) corresponding to 1.00 pm and thereafter a steady declining trend was observed.

PAR transmittance for the unpruned stands of relatively high planting density (2500 trees/ha) followed a characteristic diurnal pattern. The PAR gradually increased from 9.00 am to 1.00 pm and steadily declined thereafter. The peak PAR transmittance value of 31 % was noticed at 1.00 pm. The pruned stands of same planting density also showed the similar pattern of PAR transmittance. However, PAR transmittance was higher for the pruned stands as compared to the unpruned stands (Table 10). For instance, PAR transmittance during the mid-day was around 38% for the pruned stand while it was 31 % for the unpruned stand.

The unpruned stands of relatively low planting density (1250 trees ha-1) showed a higher PAR transmittance during early morning hours from 9 am to 11 am with the peak value of 31.17 % (11.00 am) and thereafter declining trend in the PAR transmission was observed. While the pruned stands followed the similar pattern of PAR distribution with peak value to the extent of 42 % which was observed at 1.00 pm (Table 10).

The pruned stands of low planting density (625 trees/ha) showed higher PAR transmittance during mid-day from 12.00 noon to 2.00 pm with the peak value of 54 % corresponding to 1.00 pm. While the unpruned stands represented more or less uniform distribution of PAR as that of pruned stand with peak transmittance value of 50% which was recorded at 1.00 pm (Table 10).

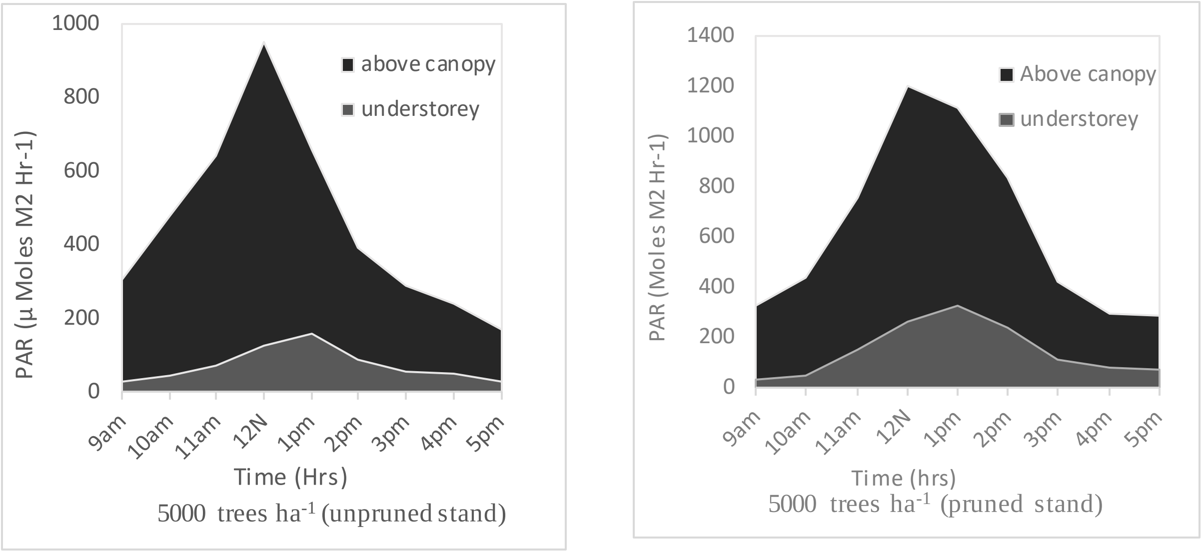
4.3.3. Light extinction coefficient (K)

$$I=I_0\, e^{-0.382\, LAI} \qquad (R^2= 0.948)$$

There was a strong relationship (R^2=0.948) between the LAI and PAR transmittance. The PAR transmittance followed Beer Lambert's law and extinction coefficient (K) value explains the average projection area of canopy elements into the horizontal surface. The K value for *Acacia mangium* stand was estimated to be 0.382. This lower K value of *Acacia mangium* stand indicating a canopy structure with erect leaves. The lower K value also signifies that there were more gaps in the canopy due to the smaller and more erect of leaf elements, which in turn allows the deep penetration of solar radiation into the understorey of the plantation.

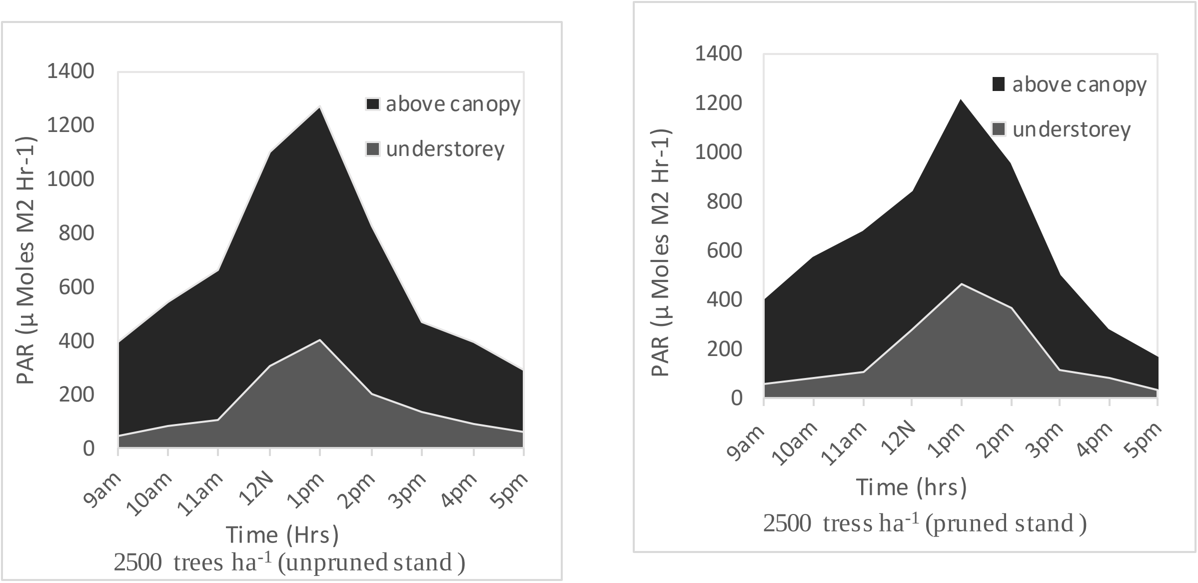
Table 10. Effect of planting density and pruning levels on PAR transmittance in *Acacia mangium* stand at Thiruvizhamkunnu, Kerala, India

	PAR transmittance (%)								
Planting density (trees ha^{-1})	9 am	10 am	11 am	12 noon	1 pm	2 pm	3 pm	4 pm	5 pm
5000 (unpruned stand)	8.81	9.46	11.02	13.16	24.27	22.93	19.77	19.67	15.1
5000 (pruned stand)	9.16	11.07	20.00	21.88	29.27	28.63	26.8	25.17	25.06
2500 (unpruned stand)	12.46	15.8	15.74	28.06	31.47	24.74	28.37	21.89	20.54
2500 (pruned stand)	13.19	13.94	15.08	33.25	38.35	37.77	22.33	29.66	18.89
1250 (unpruned stand)	29.07	30.04	31.17	26.92	19.12	25.69	24.79	18.22	17.52
1250 (pruned stand)	34.28	37.75	35.43	40.51	42.38	29.94	35.28	26.68	19.75
625 (unpruned stand)	39.33	45.78	47.46	49.29	50.82	42.58	40.96	45.26	38.31
625 (pruned stand)	42.88	39.33	38.53	49.47	54.72	48.03	44.83	48.12	43.05



5000 trees ha^{-1} (unpruned stand)

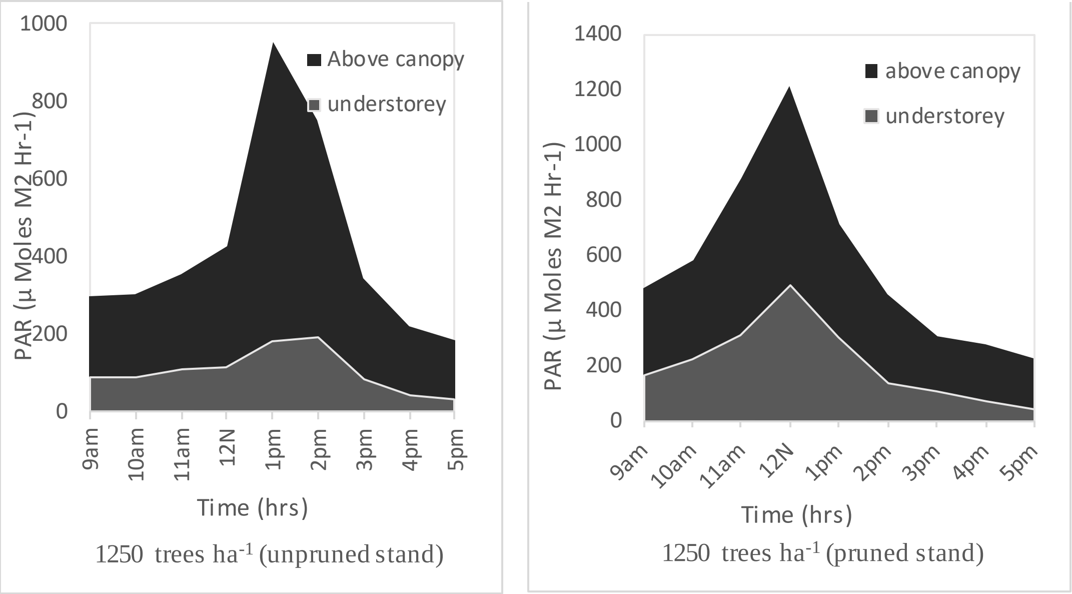
5000 trees ha^{-1} (pruned stand)



2500 trees ha^{-1} (unpruned stand)

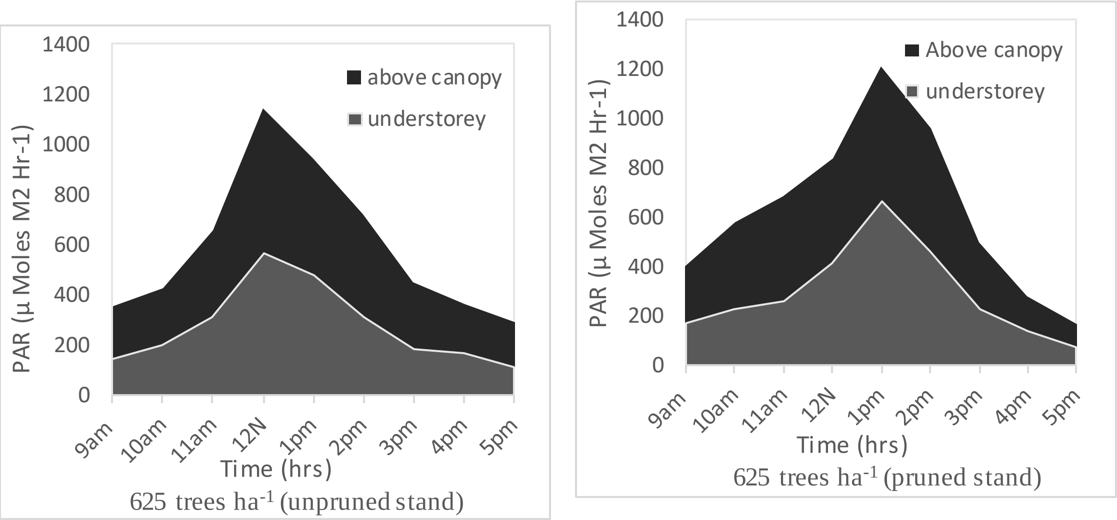
2500 tress ha^{-1} (pruned stand)

Fig 18a. Understorey PPFD levels for *Acacia mangium* stand as influenced by the planting density and pruning at Thiruvizhamkunnu, Kerala, India



1250 trees ha^{-1} (unpruned stand)

1250 trees ha^{-1} (pruned stand)



625 trees ha^{-1} (unpruned stand)

625 trees ha^{-1} (pruned stand)

Fig 18b. Understorey PPFD levels for *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

4.4. BIOMETRIC OBSERVATIONS

The data on DBH, height of trees and aboveground standing biomass as influenced by the planting density and pruning are given in Table 11.

4.4.1. Diameter at breast height (DBH)

Planting density significantly influenced the growth of *Acacia mangium* (Table 11). It was observed that the mean diameter of *Acacia mangium* significantly increased with decreasing planting density. The DBH shows a variation from 0.137 m to 0.196 m as the density varied from the higher to the lower density classes. Low density stand had higher DBH (0.196 m), while high density stand had lower DBH (0.136 m). Pruning had no significant effect on DBH. However, unpruned stand had higher DBH (0.175 m) as compared to pruned stand (0.159 m).

4.4.2. Height

Tree height was significantly different between the planting densities. The tree height was found to be maximum (19.69 m) in the relatively wide spaced stands (1250 trees/ha) and minimum in the high density stand (16.84 m) (Table 11). Pruning had no significant effect on tree height. However, unpruned stand had greater tree height (18.51 m) as compared to pruned stand (17.83 m).

4.4.3. Aboveground standing biomass

The total standing aboveground standing biomass of each tree was (stemwood+branchwood +foliage) computed based on the allometric equation, ranged from 76.98 to 196.19 kg tree^{-1} (Table 11). The widely spaced stands (625 trees ha^{-1}) had the highest biomass accumulation and it showed a decreasing trend with an increasing stand density. On a stand level, however, total biomass accumulated (stemwood+branchwood+foliage) showed a reverse trend as it increased with an increasing stand density (Table 11). Pruning and planting density together had no significant effect on aboveground standing biomass.

Pruning up to 50% of tree height reduced the biomass accumulated per individual tree (31.04 % for pruned trees) (Table 11). The widely spaced stands showed a substantial decline in biomass with respect to pruning when compared to that of the closely spaced ones.

4.4.4. Water use efficiency (WUE)

WUE estimated from the carbon isotope discrimination ($\Delta^{13}C$) values (Table 11) showed no significant differences between the various planting densities and pruning treatments. Despite being on par, the WUE values increased with decreasing planting density, which in turn ranged from 22.79 ‰ to 23.79 ‰ (Fig. 19). Pruning and its interaction with planting density treatments had no significant effect on the WUE.

Table 11. Effect of planting density and pruning on tree growth, biomass and water use efficiency (WUE) in *Acacia mangium* stand at Thiruvizhamkunnu, Kerala, India

Plant density (trees/ha)	Height (m)	DBH (m)	Aboveground standing biomass		carbon isotope discrimination (‰)
			(kg/tree)	(Mg/ha)	
5000	16.84^{c}	0.137^{d}	78.52^{d}	392.60^{a}	22.79
2500	17.91^{c}	0.150^{c}	96.90^{c}	242.25^{b}	23.55
1250	19.69^{a}	0.184^{b}	161.75^{b}	202.18^{c}	23.64
625	18.23^{b}	0.196^{a}	195.16^{a}	121.97^{d}	23.79
Pruning					
Unpruned	18.51	0.175^{a}	148.66^{a}	266.85	23.46
50% pruning	17.83	0.159^{b}	117.62^{b}	203.97	23.43
Spacing X Pruning	ns	ns	ns	ns	ns

Values with same superscript do not differ significantly
ns-not significant

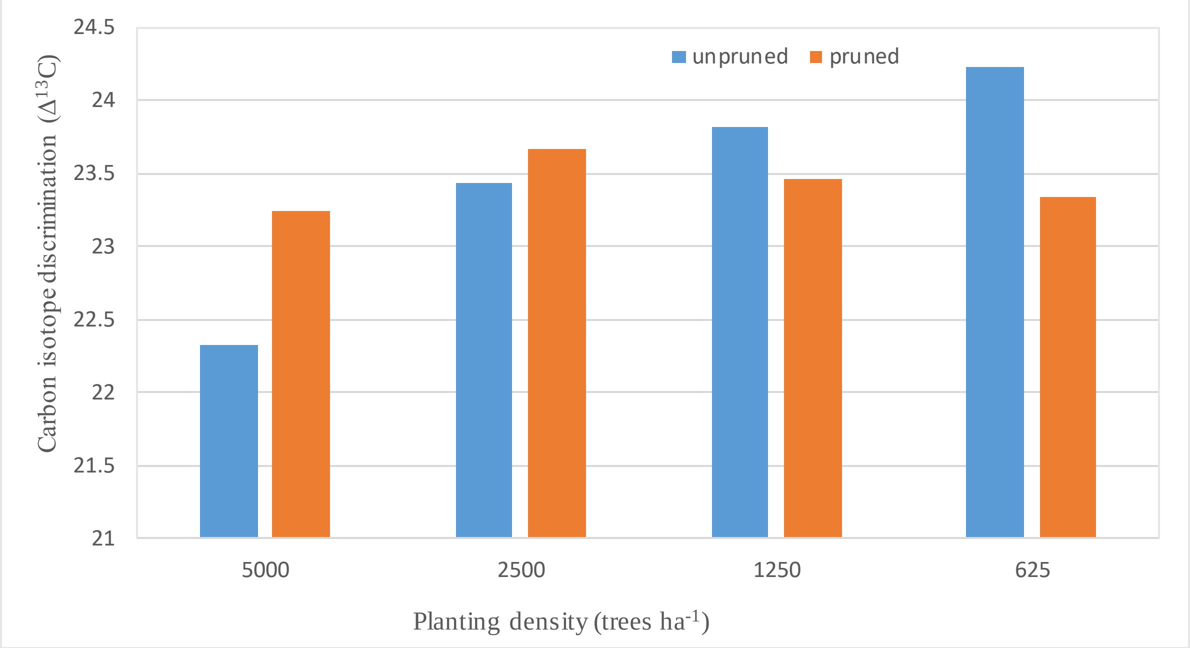


Fig 19. Carbon isotope discrimination ($\Delta^{13}C$) values of *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

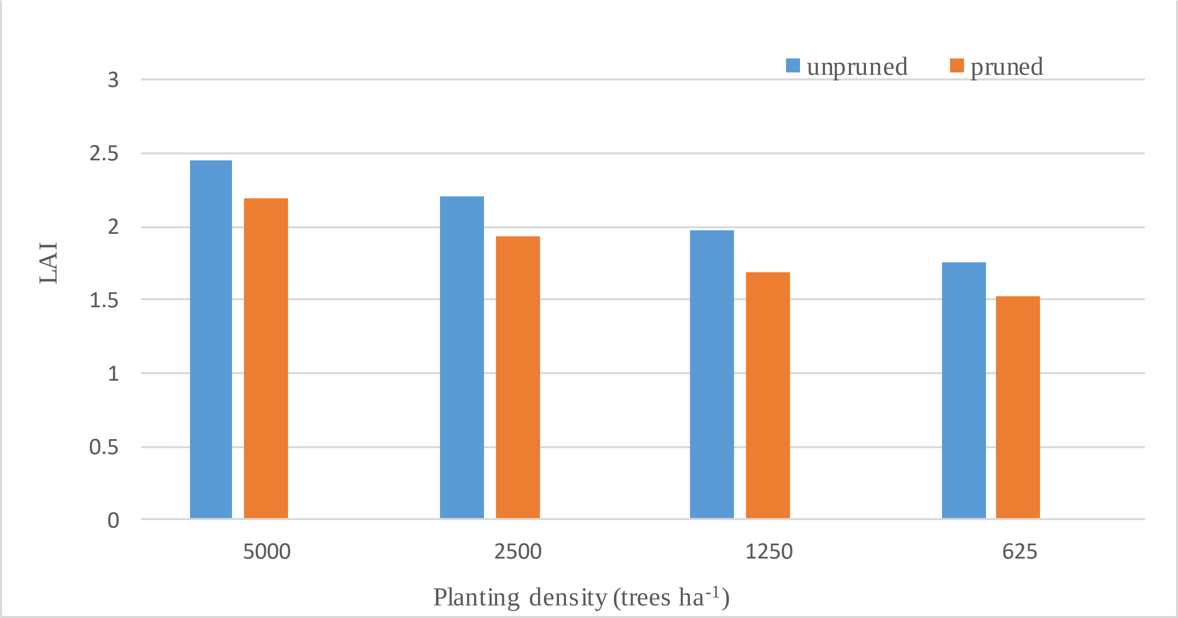


Fig 20. The stand leaf area index of *Acacia mangium* stand as influenced by planting densities and pruning at Thiruvizhamkunnu, Kerala, India.

4.4.5. Stand leaf area index

The leaf area index of *Acacia mangium* stand is presented in Table 12 and Fig. 20. The LAI showed a variation from 1.76 (pruned stands with 625 trees/ha) to 2.45 (unpruned stands with 5000 trees/ha). Leaf area index exhibited an increase with increasing stand density. However, stand pruning had resulted in modest reductions in LAI for all planting densities treatments.

Table 12. Stand leaf area index of *Acacia mangium* stand as influenced by planting density and pruning at Thiruvizhamkunnu, Kerala, India

Planting density (trees/ha)	unpruned stand	pruned stand
5000	2.45	2.19
2500	2.21	1.93
1250	1.97	1.69
625	1.76	1.52

4.5. CORRELATIONS AMONG MICROCLIMATE VARIABLES AND BIOMETRIC OBSERVATIONS

4.5.1. Correlations between leaf area index (LAI) and microclimate variables

The correlation between LAI and microclimate variables are represented in Table 13. LAI was negatively correlated with PAR at 5 m and 10 m above the ground level. LAI was negatively correlated with the air temperature at 5 m and 10 m above the ground level and also with soil temperatures at 5 cm, 10 cm and 20 cm depth. LAI did not show any significant correlation with the relative humidity and CATD. LAI was positively correlated with soil moisture content (SMC) at 5 and 10 cm depths but it was negatively correlated at 20 and 30 cm depth. LAI showed the negative correlation with relative water content and evapotranspiration

4.5.2. Correlations between soil temperature and soil moisture content

The correlations between soil moisture content and soil temperature are given in Table 14. Soil moisture at surface (5 and 10 cm depth) and sub-surface (20 and 30 cm depth) levels was negatively correlated with soil temperature at 5, 10 and 20 cm depths.

Table 14. Correlations between the soil temperature and soil moisture content

	SMC (5 cm)	SMC (10 cm)	SMC (20 cm)	SMC (30 cm)	ST (5 cm)	ST (10 cm)
SMC (10 cm)	0.86^*					
SMC (20 cm)	0.79^*	0.81^*				
SMC (30 cm)	0.79^*	0.79^*	0.94^*			
ST (5 cm)	-0.67^*	-0.62^*	-0.54^*	-0.56^*		
ST (10 cm)	-0.81^*	-0.77^*	-0.68^*	-0.67^*	0.95^*	
ST (20 cm)	-0.84^*	-0.79^*	-0.68^*	-0.68^*	0.96^*	0.95^*

*- correlation significant at 0.05 level

Abbreviations: ST - soil temperature and SMC -soil moisture content,

Table 13. Correlations between leaf area index (LAI) and microclimate variables

	AT (5 m)	AT (10 m)	ST (5 cm)	ST (10 cm)	ST (20 cm)	RH (5 m)	RH (10 m)	PAR (5 m)	PAR (10 m)	SMC (5 cm)	SMC (10 cm)	SMC (20 cm)	SMC (30 cm)	CATD	RWC	ET
LAI	-0.24*	-0.30*	-0.29*	-0.27*	-0.30*	0.13*	0.028	-0.28*	-0.27*	0.24*	0.16*	-0.19*	-0.15*	-0.06	-0.13*	-0.18*

*- correlation significant at 0.05 level

Abbreviations: AT - air temperature , RH - relative humidity, PAR -photosynthetic active radiation, ST - soil temperature SMC -soil moisture content, RWC-relative water content, ET – evapotranspiration and CATD-canopy-air temperature differential.

4.5.3. Correlations between CATD with ET, RWC and SMC

The correlation between ET, RWC, CATD and SMC are presented in Table 15. Among these microclimate variables, CATD showed negative correlation with RWC and SMC at various depths. CATD showed a positive correlation with ET.

Table 15. Correlation between CATD with ET, RWC, and SMC

	ET	RWC	CATD	SMC 5 cm	SMC 10 cm	SMC 20 cm
RWC	-0.62^*					
CATD	0.54^*	-0.56^*				
SMC 5 cm	-0.74^*	0.68^*	-0.57^*			
SMC10 cm	-0.71^*	0.69^*	-0.50^*	0.50^*		
SMC 20 cm	-0.68^*	0.76^*	-0.59^*	0.59^*	0.79^*	
SMC 30 cm	-0.66^*	0.75^*	-0.60^*	0.60^*	0.79^*	0.79^*

*- correlation significant at 0.05 level

Abbreviations: ST - soil temperature, SMC -soil moisture content, RWC-relative water content, ET –evapotranspiration and CATD-canopy-air temperature differential.

4.5.4. Correlation between soil moisture content and microclimate variables

The correlations between soil moisture content and microclimate variables are represented in Table 16. Relative humidity and relative water content were positively correlated with the soil moisture content at various depths while, evapotranspiration (ET), canopy–air temperature differential (CATD), air temperature (5 and 10 m above the ground level), PAR (5 and 10 m above the ground level) and soil temperature at various depths indicated a negative correlation with soil moisture content.

Table 16. Correlation between soil moisture at various depths and microclimate variables

	AT 5 m	AT 10 m	RH 5 m	RH 10 m	PAR 5 m	PAR 10 m	ST 5 m	ST 10 m	ST 20 m	RWC	CATD	ET	SMC 5 cm	SMC 10 cm	SMC 20 cm
SMC 5 cm	-0.70*	-0.65*	0.68*	0.64*	-0.67*	-0.67*	-0.82*	-0.81*	-0.84*	0.68*	-0.57*	-0.74*			
SMC 10 cm	-0.66*	-0.62*	0.64*	0.59*	-0.62*	-0.62*	-0.77*	-0.77*	-0.79*	0.69*	-0.50*	-0.71*	0.86*		
SMC 20 cm	-0.58*	-0.50*	0.63*	0.64*	-0.54*	-0.54*	-0.68*	0.68*	-0.68*	0.76*	-0.59*	-0.68*	0.79*	0.81*	
SMC 30 cm	-0.56*	-0.49*	0.64*	0.66*	-0.55*	0.56**	-0.66*	-0.67*	-0.67*	0.75*	-0.60*	-0.66*	0.79*	0.79*	0.94*

*- correlation significant at 0.05 level

Abbreviations: AT- air temperature , RH - relative humidity, PAR -photosynthetic active radiation, ST - soil temperature SMC -soil moisture content, RWC-relative water content, ET – evapotranspiration and CATD-canopy-air temperature differential.

4.5.5. Correlations between growth parameters and microclimate variables

The correlations between growth parameters and microclimate variables are presented in Table 17. The growth parameters such as diameter, height and biomass were positively correlated with the air temperature (at 5 m and 10 m height), PAR (at 5 and 10 m height), soil temperature, relative water content, evapotranspiration and soil moisture (at 20 and 30 cm depth). But they showed a negative correlation with the soil moisture content at 5 and 10 cm depth. Growth parameters did not show any significant correlation with the relative humidity and CATD.

Table 17. Correlation between growth parameters and microclimate variables

	Diameter	Height	Biomass
AT 5 m	0.24^{*}	0.24^{*}	0.25^{*}
AT 10 m	0.19^{*}	0.19^{*}	0.20^{*}
RH 5 m	0.03	0.03	0.03
RH 10 m	0.07	0.07	0.07
PAR 5 m	0.24^{*}	0.24^{*}	0.25^{*}
PAR 10 m	0.23^{*}	0.23^{*}	0.24^{*}
ST 5 cm	0.29^{*}	0.29^{*}	0.29^{*}
ST 10 cm	0.29^{*}	0.29^{*}	0.28^{*}
ST 20 cm	0.30^{*}	0.30^{*}	0.31^{*}
SMC 5 cm	-0.16^{*}	-0.16^{*}	-0.17^{*}
SMC 10 cm	-0.11^{*}	-0.12^{*}	-0.12^{*}
SMC 20 cm	0.15^{*}	0.15^{*}	0.16^{*}
SMC 30 cm	0.13^{*}	0.13^{*}	0.14^{*}
RWC	0.25^{*}	0.25^{**}	0.24^{*}
CATD	-0.05	-0.05	-0.06
ET	0.19^{*}	0.19^{*}	0.19^{*}

*- correlation significant at 0.05 level

Abbreviations: AT - air temperature , RH - relative humidity, PAR -photosynthetic active radiation, ST -soil temperature SMC -soil moisture content, RWC-relative water content, ET –evapotranspiration and CATD-canopy-air temperature differential.

Discussion

5. DISCUSSION

The salient findings of the study involved the evaluation of thermal, radiative, moisture regimes and water use efficiency under the different planting densities and pruning levels in *Acacia mangium* stand are discussed hereunder.

5.1. THERMAL ENVIRONMENT

5.1.1. Temperature

Temperature is a crucial factor while determining the rates of biochemical reactions and it has a strong influence on plant and root growth (Jimenez *et al.*, 2007; Facelli and Pickett, 1991). It affects the cambial activity, cell differentiation and many other physiological parameters (Oribe *et al.*, 2001; Begum *et al.*, 2007; Rossi *et al.*, 2008).

The air temperature was invariably the highest in the open area when compared to that of *A. mangium* stand irrespective of planting densities throughout all seasons (Table 2). The lower air temperature inside the *Acacia mangium* stand is due to the process of absorption, scattering and reflection of the incoming solar radiation thereby reducing the amount of energy penetrating into the lower canopy which eventually reaches the soil surface. Groot and Carlson (1996) found that there is an average air temperature difference of nearly 3° C between forest and open area. Similarly, Anderson *et al.* (2007) also found that mean air temperature of the open area was 3 to 4 °C higher than that of the tree cover area.

It was observed that the air temperature did not vary much between 5 and 10 m above the ground level during the study period. Usually in the forest canopy, microclimate parameter like temperature has a vertical gradient. Woodruff *et al.* (2002) observed an elevation of 67 % in the mean temperature in the low density planting than that in the high density planting at the canopy height of 1 m but no significant variation was noted at 3 m and 5 m canopy heights.

Similar observations were also noticed by Zhang *et al.* (2013) in the *Robinia pseudoacacia* plantation, where the air temperature didn't show any significant changes at different heights above the ground surface. However, a study by Zweifel *et al.* (2002) observed a temperature variation of about 1°C approximately at every 4 m distance from the upper to lower canopy in *Picea abies* forest. Probably these variations could be more manifested in higher latitudes where temperature fluctuations have significant effect on growth.

In the present study, it was observed that the air temperature significantly decreases with increasing planting density in all seasons except monsoon (Table 2). During the day, solar radiation penetrates the plant canopy and is absorbed by the leaves, which in turn heat the leaves as well as the air within the canopy. The radiation which does not get absorbed by the canopy eventually reaches the ground where most of it is absorbed, leading to heating up of the soil surface. As the soil surface warms, heat is both conducted down into deeper soil layers as well as transferred to the air immediately above the soil. Therefore, the air temperature above the ground is strongly affected by the amount of sunlight that is able to penetrate to the canopy and soil characteristics. The high density stands absorb more momentum and therefore allows less vertical mixing of air within the canopy and thus act to keep the near surface air cool (Raupach *et al.*, 1996). Whereas the lower planting density stands allow more turbulent mixing of air within the canopy layer and this results in greater temperature. The air temperature at higher vertical levels has higher values than near the soil surface. This is because the more sunlight is absorbed near the top of the canopy which results in an increased canopy and air temperature leading to the establishment of an air temperature vertical gradient. However, such differences were not pronounced in the present study.

The air temperature was not affected by pruning treatments. This may be due to the regrowth and canopy establishment by *Acacia mangium* stand resulting in stabilisation of air temperature inside the plantation. Similar findings have been reported by Newaj *et al.* (2007) in an *Albizia procera*-based agroforestry system and Pratap *et al.* (2003) in a 14 year old mango orchard.

5.1.2. Soil temperature

Soil temperature is an important parameter in plant growth, such as seed germination and early season growth which are highly correlated with the daily maximum temperature of soil rather than air temperature (Green *et al.*, 1984). Soil temperature recorded was highest in the open area while the lower under tree cover (Table 3). Differences were significant in all seasons except than that in the monsoon season.

Soil temperature was lower under the *Acacia mangium* canopy when compared to that of the open area. It is due to shading and is determined by the soil surface heat energy balance (Fedema and Freire, 2001; Jacobs *et al.*, 2011). For example, changes in vegetation types or planting density could change the soil temperature by affecting the energy flux (Jiménez *et al.*, 2007). In the present study, soil temperature increased with decrease in the planting density (Table 3) and recorded findings are consistent with many studies (Belsky *et al.*, 1989; VandenBeldt and Williams, 1992; Johnson, 1995). Sinoquet and Bonhomme (1995) in a 7 year old *Acacia mangium* plantation observed that the mean soil temperature at 0-20 cm depth under plantation was lower than open condition by 2^{o} C and the effect of the canopy on lowering the temperature was more obvious in the dry season than in the wet season.

In the present study, among the planting densities, soil temperature increased with a decrease in plant density irrespective of seasons (Table 3). This is probably due to the fact that the solar radiation was intercepted or reflected by the high density stand canopy (Table 10) which in turn reduced the radiation absorbed by the soil thereby resulting in the lower soil temperature (Facelli *et al.*, 1991; Scull, 2007). Furthermore, the interactions between the underlying surface and atmosphere can have an impact on the lower atmospheric circulations and affects the microenvironment.

It was observed that pruning significantly affected the soil temperature only during the post-monsoon season (Table 3). Pruning operation is generally done prior to the monsoon season and hence the difference in canopy is more pronounced during this time. Shangwei *et al.* (2009) revealed that pruning increased the soil temperature compared to the unpruned trees due to the opening of the canopy that led to the increased absorption of PAR by the soil surface that in turn increased the soil evaporation and thereby resulting in a high soil temperature. Similarly, Newaj *et al.* (2007) studying an *Albizia procera* based agroforestry system, found that soil temperature was significantly higher under the canopies of pruned trees than the unpruned trees.

5.1.3. Canopy-air temperature difference (CATD)

The use of CATD to detect the plant moisture stress is based on two assumptions (Jackson *et al.*, 1982). First, when plenty of water in the soil, tree will transpire at its maximum potential rate, resulting in leaf temperature lower than the air temperature. Second, as water deficit increases, the transpiration declines and leaf temperature rises relative to the air temperature. A quantitative index of plant water status for irrigation scheduling in plantation can be developed by the potential use of these relationships.

In the present study, it was observed that CATD was greater in the high planting density and lower in the low planting density (Table 4) during the summer and pre-monsoon season. It is likely because of water deficit in the high planting density, reduce the tree water use by increasing the surface resistance and reducing the transpiration rate, and for this reason, their maximum temperature markedly exceeded an ambient temperature as compared to that of low planting density. This effect was more pronounced during the summer followed by pre-monsoon season when compared to that of the monsoon and post-monsoon season.

No significant changes in CATD was observed among the different planting densities due to rainfall and lower temperature. It is because of onset of canopy intensive growth and availability of sufficient amount of water across the plantation for canopy cooling through transpiration leads to lower the leaf temperature than the ambient temperature during the monsoon and post-monsoon season.

5.2. MOISTURE ENVIRONMENT

5.2.1. Relative humidity

Significant variation in the relative humidity has been observed among the varying planting densities for all the seasons. It was found that relative humidity increased with increasing planting density (Table 5). Physiological processes such as photosynthesis, transpiration, respiration and soil evaporation produce or deplete CO_2 and water vapour in the canopy atmosphere relative to the bulk atmosphere. An even canopy surface, low wind speed, small plant stature and increased plant density are all factors affecting boundary layer resistance of the canopy (Monteith and Unsworth, 1990; Landsberg and Gower, 1997). Canopy boundary layers may affect the atmospheric mixing, resulting in different concentrations of gases within the canopy than above (Brooks *et al.*, 1997). Within the canopy of the high-density stands, H_2O that is transpired do not immediately mix with the bulk atmosphere, allowing a substantial build-up. These concentrations could be substantially larger than those within the low density stands. Green *et al.* (1995) found that within the canopy of Sitka spruce, the wind speed increased with spacing which causes a simultaneous increase in the turbulence parameters, such as tangential momentum stress and turbulence velocity components. This suggests that the capacity for vertical mixing and turbulent exchange between the canopy and the atmosphere decreases as density increases. This alters the canopy boundary layer conductance. The decreased canopy boundary layer conductance of the high-density stands, in turn, results in the significantly higher water vapour concentrations than that in the low-density stands, presumably in response to the decreased plant transpiration and soil evaporation.

Stomata may respond to the increased humidity by opening more or remaining open longer throughout the day resulting in the increased photosynthesis as well as photosynthetic water use efficiency (Hall and Scurlock, 1993; Harrington *et al.*, 1994; Waring and Winner, 1996). In short, the increased stocking density may enhance the humidity within a stand. Koech and Whitebread. (2000) reported that in *Leucaena leucocephala* alley cropping system, reported that the relative humidity decreased with increasing alley width. Similar findings have been reported by Pratap *et al.* (2003) in a 15 year old red pine stand. On the other hand, Caramori *et al.* (2003) found that the variation of humidity in both dense and open canopy have very little difference.

There is a suggestion that pruning can change the RH inside the canopy since a considerable number of branches and leaves are removed. Interestingly in present study, relative humidity was not significantly influenced by pruning treatments during the study period. This may be due to the sufficient regrowth had been produced by the canopy of *Acacia mangium* leading to stabilisation of relative humidity inside the plantation. Similar results was also found for seven year old citrus plantation (Morales and Davies, 2002).

5.2.2. Soil moisture content (SMC)

The soil moisture content was significantly higher under the *Acacia mangium* stand compared to that of the open conditions (Table 6 and Fig. 10-13). A higher top soil moisture under the woody canopies than in the treeless sites appears to be a common pattern. This may be due to the rapid evaporation of soil moisture from the exposed surface layer as compared to that of the vegetated areas. Soil moisture content at 0 to10 cm depth during the end of the rainy season was found to be twice as high as under the *F. albida* canopies as that in the open due to the lower evapotranspiration (Charreau and Vidal, 1965).

Dancette and Poulain (1969) found that soil moisture was higher under the *F. albida* trees than in the open in the top 120 cm depth. Water reaches deeper horizons under the trees than in the open because of macro pores and better infiltration.

In the present study, the soil moisture content at surface levels (5 cm and 10 cm depth) was higher at the high planting density and least in the low planting density (Table 6). The presence of vegetation directly affects the soil-moisture regime and thus the hydrological behaviour of a plantation. Soil moisture is also influenced by vegetation density. Locations with the denser vegetation tended to have higher soil moisture in shallow depths. This is because the dense vegetation cover might intercept more incoming solar radiation and greater reduction of soil evaporation and a smaller increase of transpiration resulting in a less net soil water loss (Marshall and Holmes, 1988). At subsurface levels (20 and 30 cm depth), the trend reversed with the soil moisture content and was higher at the low density as compared to that of the high planting density. Similar results were also found for 15 year black locust plantation (Wang *et al.,* 2002), shade trees in tea garden (Pereira, 1959), *Fagus sylvatica* plantation (Stiptsov and Botev, 1995) and Scot pine (*Pinus sylvestris*) plantation (Rodriguez-Calcerrada *et al.,* 2008). Although higher planting density reduces the radiation at the soil surface, it increases the radiant energy absorbed by the trees leading to the accelerated soil moisture depletion through transpiration (Rey, 1999). Larger canopies reduce the soil moisture due to their exacerbated competition and more extensive exchange surface between the foliage and air. This is especially true towards the later part of the rainy season when rainfall events become frequent, less intense and temperature rises. However, opposite trends have been reported for a 17 year old *Ailanthus triphysa* plantation (Rakesh, 2009). Contrary to all of these, there are reports of soil moisture not being affected by planting densities. A study in an *Acacia saligna* agroforestry system planted at densities of 2520, 1330, 840 trees/ha, was reported that tree planting density did not affect the soil moisture content and productivity (Sauerhaft *et al.,* 1999).

In present study, it was observed that the pruning did not affect the soil moisture content at 5 cm and 10 cm depth in all seasons except the post-monsoon season (Table 6). In an agroforestry system, it was revealed that the soil moisture content of shallow levels was reduced by pruning (Shangwei *et al.,* 2009). This is because of the increased soil evaporation due to the opening of the canopy that leads to lowering of the soil moisture content in shallow depth. It appeared that in present study pruning did not open up the canopy to create such an effect. At the subsurface level (20 cm and 30 cm depth), pruning had no significant effect on soil moisture except the post-monsoon season (Table 8). A similar result was also found for Li *et al.* (2012) in an apple plantation, where the soil moisture content at subsurface levels had no significant differences between the pruned and unpruned trees. This is because of pruning of the tree canopy did little to limit the water demand of tree component, resulting in little or no recharge to the soil profile (Jackson *et al.,* 2000).

5.2.3. Relative water content (RWC)

Relative water content varied significantly between the planting densities. The lower relative water content was observed in the high density stand and higher relative water content was observed in the low planting density (Table 7). However in the monsoon and post monsoon seasons, the relative water content of all planting densities was more or less similar due to the rainfall and lower temperature. Similar results was also found for olive trees, which were grown at different planting densities (Guerfel *et al.,* 2010). This is due to the lower evapotranspiration rate and higher soil moisture content that could contribute to maintain a better water status as observed there was a positive correlation between the soil moisture content and relative water content (Table 16). Some results indicated that RWC decreases slightly when soil moisture content is low and this decreasing is even more remarkable when soil moisture is under a critical value (Saifuddin *et al.*, 2010).

In present study, the RWC was significantly higher under the pruned stands compared to the unpruned stands. The removal of lower and inefficient branches increase the capability to maintain the higher photosynthesis process and reduction of transpiration lead to the higher relative water content under pruned stands.

5.2.4. Evapotranspiration

In current study, it was observed that evapotranspiration rate in the high density stand is lower as compared to that in the low density stand (Table 8 and Fig. 15). Similar results were also obtained for *Eucalyptus grandis* plantation and tulip trees (Vandervales, 1999) which may be due to the reduced radiation and stomatal conductance (Eastham and Rose, 1988). Trees influence the evapotranspiration through effects on microclimate and soil water content (Ong *et al.*, 2007; Liu *et al.*, 2008). The microclimatic factors most likely to be modified are solar radiation receipts at ground level and wind speed (Wallace, 1996). Evapotranspiration also have influenced by the soil nutrients and moisture conditions (Sosebee *et al.*, 1971; Ovaska *et al.*, 1992; McJannet *et al.*, 2001; Zeppel *et al.*, 2004), humidity of air adjacent to leaves (Whitehead *et al.*, 1984; Jarvis and McNaughton, 1986) and the supply of water from conducting stem tissue (Wulleschelgar *et al.*, 1998). However, aerodynamic factors such as wind speed are less important in the relatively closed canopies. Hence, solar radiation is the major factor that influences the evapotranspiration (Yang *et al.*, 1990; Zhang *et al.*, 2010). Contrary to this, there are reports mentioning that the greater evapotranspiration under the closer spacing due to the well exposed leaf area at the top of the plants (Papadopoulos and Ormond, 1988).

In the present study, evapotranspiration was not affected by the pruning treatments except in post-monsoon season (Table 8). Rapid reductions in photosynthetic leaf area following shading, disease or defoliation have the potential to dramatically alter evapotranspiration, although not necessarily in proportion to the leaf area reduction (Pepin *et al.*, 2002 and Whitehead *et al.*, 1996).

The removal of leaves reduces the amount of light intercepted and rates of evapotranspiration (Bredenkamp *et al.*, 1980; Pinkard and Beadle, 1998; Pinkard *et al.*, 2004; Forrester *et al.*, 2010). On contrast to above studies, there are reports to reveal that the removal of about 45% (Quentin *et al.*, 2011) or 60% (Quentin *et al.*, 2012) of the leaf area of *Eucalyptus globulus* tree crowns results in the higher transpiration per unit leaf area while pruning 75% of the leaf area of *Eucalyptus nitens* (200 trees ha^{-1} trees) reduced transpiration by about 16% but it increased the transpiration per unit leaf area, after 2–3 years of pruning.

5.3. RADIATION ENVIRONMENT

5.3.1. **Photosynthetically Active Radiation (PAR)**

Planting density has a profound influence on the understorey PAR availability. It was found that the decrease in planting density can bring about an increase in PAR (Table 9 and Fig. 16-17). Canopy structure, stand density, row orientation, leaf area index, site, latitude, season and spectral quality of light are some of the major factors that decide the extent of solar radiation penetrating into the understorey (Baldocchi and Ollineau, 1994). Among these, planting density plays an important role on the quantity and quality of the understorey PAR availability. For instance, Starostin and Maslakov (1989) observed that the PAR transmittance beneath the canopy was 90% in the lower planting density. Modification in the crown geometry as contributed by the variation in the spacing may also modify the understorey light environment. Variation in the canopy structure between species and consequent changes in the PAR interception has also been observed. Plantation of high density stand intercepts substantially more radiation than low density stand (Kumar *et al.,* 2001). They observed a strong interspecific difference in the understorey of *A. auriculiformis* intercepting much of solar radiation while *Ailanthus triphysa* intercepted much lesser PAR.

A study by Akers *et al.* (2013) in a loblolly pine (*Pinus taeda*) plantation observed that interception of PAR was significantly greater for the stands planted at the higher densities while, live crown length and crown ratio were significantly greater for the stands planted at the lower densities which support the idea that the higher density stands intercept PAR more efficiently than that of the lower density stands. As leaf area develops, radiation interception by the leaves increases (Mathew *et al.,* 1992). LAI was higher for the high density *Acacia mangium* stand than that of the low density stand because of the much larger leaf area which produces a denser canopy resulting in greater shading.

One of the major practical implication of this study is the realisation of PAR ranges under various planting densities for *Acacia mangium* which has a strong bearing on understorey productivity in polyculture systems involving *Acacia mangium.*

Tree pruning is an important silvicultural operation which helps in the improvement of the understorey light environment. In present study, pruning generally increased the understorey PAR availability. Pruning temporarily opens up the canopy which improves the photosynthetic flux density at the understorey level. However, this was not observed in the present study.

5.3.2. Light extinction coefficient (K)

Light extinction coefficient (K) is a parameter that describes the exponential decrease in the light intensity as it passes through a canopy. The light extinction characteristics of crowns differed among the species in relation to the several traits such as leaf angle and branch architecture.

In present study, the estimated extinction coefficient (K) value was 0.382, which generally corresponds to those of vertically inclined leaves. This lower K value of *Acacia mangium* explains that the lower interception of light by trees leads to reduce competition not only for light but also for water because transpiration is directly linked to the quantity of radiation intercepted by the canopy (Brown and Parker, 1994).

Also, the lower K value of *Acacia mangium* stand indicates a canopy structure with erect leaves, which in turn allows the deep penetration of solar radiation into the understorey of the plantation.

5.4. BIOMETRIC OBSERVATIONS

5.4.1. Planting density and growth

As can be seen from Table 11, the mean diameter of *Acacia mangium* increased with decreasing planting density which was ranged from 0.137 m to 0.196 m from higher to lower density classes. Practically, in all reports, the mean diameter of trees in the stand increases with increasing spacing (Smith, 1997). However, the magnitude of response varies with the species and growth phase of the stand. Differences on account of variation in stand density in the *A. mangium* stand were significantly observed from two years onwards by Kunhamu *et al.* (2005) in the same stand. Density induced inter-specific competition often results in size differentiation among individuals wherein smaller trees experience continued suppression. Tree height is found to be maximum in the relatively widely spaced stands (1250 trees ha^{-1}). Similar observations were also reported by Bormann and Gordon (1984) for the red alder and Cole and Newton (1987) for Douglas-fir plantations. Lanner (1985) suggested that stand density has little effect on the height growth where the stand is extremely dense or so open that trees are distinctively isolated.

5.4.2. Pruning and growth

Diameter at breast height varied significantly between pruning treatments with the unpruned stands showing higher DBH (0.175 m) compared to the pruned stands (0.159 m) (Table 11). Tree pruning generally results in reduction of growth implying that *A. mangium* might respond better to the lower pruning treatments (Kunhamu *et al.*, 2006). The removal of leaves reduces the amount of light intercepted and rates of transpiration (Forrester *et al.*, 2012, 2013; Alcorn *et al.*, 2012). This reduction in resource use can reduce growth.

It was reported that *Acacia mangium* growth is often unaffected by pruning as long as no more than about 40–50% of the length of the live crown is removed in a single pruning lift (Majid and Paudyal,1992).

Pruning had no significant effect on the height of *Acacia mangium* trees. Similar observations were also reported for *Eucalyptus pilularis* and *Eucalyptus cloeziana* (Alcorn *et al.,* 2012). Owing to the fast vertical crown expansion, trees would be able to rapidly compensate for leaf area removal without long-term reductions in growth.

5.4.3. Aboveground Standing Biomass

Aboveground standing biomass under different planting densities and pruning levels are presented in Table 11. The higher standing above ground biomass accumulation was observed for the wider spacing (195.16 kg tree^{-1}) as compared to the closer spacing (78.52 kg tree^{-1}) and it generally followed declining trend with increasing stand density at individual tree level. Silvicultural prescriptions involving stand density are often made based on the assumption that individual tree productivity is inversely related to standing density (Smith *et al.,* 1997). The lateral enlargement of crowns and overlapping of roots in closer spacing might increase competition for available resources between trees leading to a reduction in their biomass production. Total standing biomass on stand basis followed the reverse trend and it was higher in the wider spacing (121.97 kg ha^{-1}) as compared to the closer spacing (392.60 kg ha^{-1}). This is similar to findings of Kunhamu *et al.* (2005) who reported that the above ground biomass was 81.82 Mg ha^{-1} for the closer spacing and 41.39 Mg ha^{-1} for wider spacing in the same stand at 6.5 years. This is due to better resource utilisation at the closer spacing increasing the unit area biomass production.

Tree pruning up to 50 % of tree height reduced the standing biomass on per tree basis. The aboveground standing biomass in the unpruned stands was higher (148.66 kg tree^{-1}) as compared to the pruned stands (117.62 kg tree^{-1}) on per tree basis. However, this difference was not evident on per unit area basis.

It is clear from many studies that the minimum level of pruning affects growth and varies between species, while for *Acacia mangium*, growth is often unaffected by pruning if no more than 50% of lower green crown length was removed (Majid and Paudyal,1992). In general, removal of leaves reduces the amount of light interception by canopies. This reduction in resource use can reduce biomass of trees.

5.4.4. Water use efficiency

In current study, the water use efficiency estimated by carbon isotope discrimination values were non-significant among the planting densities of *A.mangium* stand (Table 11). The effect of planting density on WUE remains so far undocumented in *Acacia mangium* till date. Only a few studies have investigated how WUE responds to planting density in other woody species, leading to conflicting results.

Within the context of study site, where the water is not limiting due to precipitation leads to sufficient availability of soil moisture for plant growth. In addition, there was no significant dry period during the study period. The belowground stratification and availability of more water per unit land area, may enable the trees across the different planting densities to optimise the water use. This may be the one of a possible explanation for the similar WUE under different planting densities. In support of the current study, other works suggest that planting density had no impact on the water use efficiency. Woodruff *et al.* (2002) found that no differences in WUE between the low and high planting densities in *Pseudotsuga menziesii*. Similarly, no significant differences were also observed for the *Acacia saligna* at different planting densities (Dropplerman *et al.,* 2000) and birch seedlings grown under the elevated CO_2 conditions (Zhang *et al.,* 2008).

WUE has been related to water consumption per unit of dry matter production. In present study, even though dry matter production (aboveground biomass) varied with planting densities, WUE remains the same across planting densities.

This suggest that growth differences probably were not caused by mechanism that operates primarily through changes in availability of water that affect the photosynthetic performance. It is also possible that changes in more than one of the factors related to growth parameters like radiation, nutrients, etc. cancelled each other out. Ngugi *et al.* (2003) reported that three different 7 month old Eucalyptus clones exhibited similar water use efficiency at high, medium and low planting densities, indicating that water use and wood production were proportional.

There are implication of these results. On first, when soil conditions are favourable, increasing planting density would primarily accentuate trees competition for light; on one hand, no differences in WUE can exist due to the availability of more water per unit land area enable the trees to maximise the water use. On other hand, maximum biomass production, increasing in canopy size and consequently high water demand exhibit better stomatal regulation in order to limit the water losses, resulting into the higher WUE. Therefore one can expect a positive relation between the growth and WUE. Secondly, when soil conditions are not favourable, the growth will be reduced and increasing planting density accentuate plant competition for soil resources and increase in WUE as a consequence of water limitation results in trade-off between planting density and WUE.

Together these studies suggest that improvements in the growth may or may not be associated with water use efficiency. The proportional increases in growth and water use be evaluated strictly on species basis and on local and regional water balance. However, more work is needed to examine how the water use efficiency changes with stand development, water availability within a single site, across production gradients and under climate change scenarios.

Although our study sites are located in humid area where water is not a limiting factor, suggests that trade-offs between increased productivity and water use efficiency should be carefully considered in dryer areas and in the light of potential changes in precipitation with climate change.

Pruning had no significant effect on WUE. However, WUE were marginally lower in the pruned stands as compared to the unpruned stands. Similar observations were also reported for a five year old *Eucalptus nitens* plantation (Medhrust *et al.*, 2002). Due to the removal of shade and least efficient canopy foliage generally reduces the water use and make the most efficient use of water that is transpired (White *et al.*, 2009). However, few studies have compared WUE of the pruned and unpruned trees, so more studies will be required to examine how the magnitude and duration of pruning affects the water use efficiency between the planting densities, resource availabilities and climatic conditions.

5.5.1. Stand leaf area index and microclimate variables

In present study, the stand leaf area index decreased with a decrease in stand density (Table 12 and Fig. 20). Similar results were also found by Bhimappa, (2014) in bamboo based agroforestry systems. Minimising the competition between trees and maximising the use of available resources is central to improve yields and overall productivity in tree based systems (Cannel *et al.*, 1983). So the factors like LAI and crown development are most important for standardisation of spacing in plantations. Trees minimise the amount of solar radiation reaching to the understorey through leaf orientation and arrangements. The extent of shade varies according to the crown dimensions, tree phenology and leaf density.

5.5.1.1. *LAI influence on air and soil temperature*

Canopies with high LAIs absorb more momentum and therefore allows the less vertical mixing of air within the canopy and thus acts to keep the below canopy air cool (Raupach *et al.*, 1996). Canopies with lower LAI allow more turbulent mixing of air within the canopy sub-layer and this results in the higher temperature. These processes probably explain the observed relationship between the air temperature and the LAI (Table 13). The soil surface is heated by incoming solar radiation that penetrates the full depth of the canopy.

Heat is then conducted down into the lower soil layers, however, this process takes time and hence, soil temperature lags behind air temperature. The maximum soil temperature is higher beneath the sparser canopies because of more solar energy reaching the soil surface.

5.5.1.2. *LAI influence on relative humidity and evapotranspiration*

During the day, as the temperature rises, the vapour pressure increases, causing an increment in the vapour pressure deficit (VPD) and a decrease in the relative humidity. Under low LAI canopies, where the daytime temperature is higher and the VPD is lower, relative humidity also tends to be higher. As the VPD increases, evapotranspiration also increases as the air acquires an increased capacity to hold water vapour, creating a greater potential gradient across the leaf-air and soil-air boundaries (Garratt, 1992). This increased evapotranspiration in low LAI canopies is probably the cause of the observed trend of high LAI canopies having a higher relative humidity than low LAI canopies (Table 13). This finding is similar to that reported by Law *et al.* (2001) from observations and models of the temperate forests.

5.5.1.3. *Influence of LAI on PAR*

The amount of solar radiation absorbed by a tree canopy depends on its leaf area index (LAI). Canopies with high LAI absorb the vast majority of all incident sunlight so that the amount of sunlight reaching the ground will be less. By contrast, the low LAI canopies absorb a much less fraction of the incident solar radiation, which explains the observed relationship between LAI and PAR.

5.5.1.4. *Influence of LAI on soil moisture*

There exists a positive correlation between the LAI and soil moisture content at surface level (Table 13). This is because a large fraction of the soil moisture in the surface layer is lost through direct evaporation due to the high soil temperature and low root densities.

The negative relationship between the LAI and soil moisture content at subsurface level may be due to the high water demand associated with large canopies of the high density stands that may deplete the soil moisture content faster than areas having a sparse or no canopy (Aussenac 2000; Breshears *et al.*, 1997; Peck *et al.*, 2012; Scharenbroch and Bockheim 2007).

5.5.2. Effect of soil temperature on soil moisture

It was found that the soil temperature (ST) and soil moisture content (SMC) in the surface and subsurface soil levels (20 cm and 30 cm) were negatively correlated (Table 14). The increasing soil temperature caused by the reduction of vegetation would increase the soil evaporation affecting the water use efficiency of the plant (Liu *et al.*, 2008; Jacobs *et al.*, 2011) and simultaneously decreases the soil moisture (Zhao *et al.*, 2006). Similar observations with an increase in the temperature of surface soil corresponding to a decrease in the SMC was observed by many studies (Li *et al.*, 2010; Gao *et al.*, 2010; Zhu *et al.*, 2013). Evaporation from the surface soil is high when the soil temperature is high. The specific heat and conduction have been reported to be about 3 and 24 times higher respectively, in soil than in air respectively (Zhu *et al.*, 2013). This indicates that soil is better able to conduct thermal energy or heat from the surface soil to subsurface soil during the day. This may account for the negative relationship between soil temperature and soil moisture content in this study.

5.5.3. Relationship between CATD with ET, SMC and RWC

CATD was negatively correlated to the soil moisture content and relative water content while positively correlated to CATD (Table 15). It is generally accepted that reduction in the SMC induces a progressive reduction in photosynthesis and transpiration (Slatyer, 1967). It seems evident that this reduction in transpiration and photosynthesis can be mainly attributed to a stomatal closure, which increases the resistance in the gaseous pathway for the water vapour and CO_2 (Slatyer, 1967).

On cloudy days, water uptake by the roots can keep up with water loss by the leaves and so water loss is encumbered until water potential of the soil is reached. This reduction in the evapotranspiration can cause the greater canopy temperature than ambient temperature. This suggests that the canopy air temperature difference (CATD) could reflect the water balance of a plant (Throssell *et al.*, 1987).

5.5.4. Effect of Microclimate variables on soil moisture content

Air temperature and soil temperature were negatively correlated with soil moisture content (Table 16). An increase in the temperature of air and soil corresponds to decrease in soil moisture content (Li *et al.*, 2012). The evaporation from the soil is high when the air and soil temperature is high. The radiation not intercepted by the vegetation reaches the ground surface would cause an increase in the soil evaporation and results in the lower SMC and thereby affect the plant on water use (Liu *et al.*, 2010; Jacobs *et al.*, 2011), which leads to the negative correlation with the PAR.

Soil moisture content was positively correlated with relative water content (Table 16). It may be due to the fact that, when the moisture is limiting in the soil, the leaves are losing water more rapidly than the roots or translocation systems can supply it which results in the lower relative water content. The soil moisture content was negatively correlated with the CATD (Table 16). This is because when there is water deficient in the soil, the trees tend to reduce the evapotranspiration through reduced stomatal conductance. This results in the greater canopy temperature than the ambient temperature (Throssell *et al.*, 1987).

5.5.5. Practical implications of this study

Productivity of plantations are determined by multidimensional factors. Scientific explanations of this factors involved in this biophysical process are many and quantitative information on their role in the overall productivity is very much limited. Hence this information gathered on the microclimate parameters and their changes with density management practices will be very much helpful in designing tree based system for various end uses. The functional relation between stand density and PAR will be helpful in designing agroforestry systems involving *Acacia mangium*.

Summary

6. SUMMARY

The research work entitled 'influence of planting density and pruning on thermal, radiative and moisture regimes in *Acacia mangium* Willd. stand' was undertaken during 2014-15 at Kerala Agricultural University, Vellanikkara to study the effect of planting density and pruning on thermal, radiative and moisture regimes and also on the water use efficiency of *Acacia mangium* stand.

The salient findings are summarised below.

1. The air temperature of *Acacia mangium* stand varied significantly from the open area as well as between planting densities in all seasons except the monsoon season. In general, the maximum air temperature was recorded during the summer season followed by pre-monsoon and the minimum air temperature was recorded during the monsoon followed by post-monsoon season. The open area showed the highest air temperature in all the seasons. Among the planting densities, the air temperature was significantly higher in the low planting density and the lower in high planting density at 5 m and 10 m above the ground level irrespective of seasons. Pruning and planting density and pruning interaction had no significant effect on air temperature during the study period.

2. The relative humidity in all seasons was found significantly lower in open area as compared to that of *Acacia mangium* stand with different planting densities. During the summer season, the relative humidity was significantly higher in 5000 trees/ha and the lower in 625 trees/ha at 5 m and 10 m above the ground level. Whereas relative humidity showed statistically similar values between the planting densities during the pre-monsoon, monsoon and post-monsoon season. Relative humidity was not significantly affected by pruning and planting density and pruning interactions.

3. Soil moisture content showed an increasing trend with increase in soil depth. Soil moisture content of treeless open area was recorded the lowest value at each depth level studied. Soil moisture retention was better during the monsoon season while lowest during the summer season.

4. At surface level (5 cm and 10 cm depth), the soil moisture content was significantly higher in high planting density and the lower in low planting density in all seasons except the monsoon season. No significant variation was observed for pruning treatments during the summer, pre-monsoon and monsoon seasons. However, during the post monsoon season, the unpruned stand had significantly higher surface soil moisture content as compared to pruned stands. The interaction effect between planting density and pruning were non-significant.

5. At subsurface level (20 cm and 30 cm depth), the soil moisture content followed reverse trend with higher value being recorded at low planting density. The high planting density recorded the lowest soil moisture content. Soil moisture content was significantly higher in the pruned stand at 20 cm depth while lower under unpruned stands during the post monsoon season. However, soil moisture content did not show any significant variation for other seasons. Pruning and planting density interaction effects were absent during the study period.

6. The soil temperature showed a decreasing trend with increase in soil depth. Soil temperature was higher in the open compared to that of the *Acacia mangium* stand. The soil temperature varied significantly between the planting densities in all seasons except the monsoon season. The maximum soil temperature was observed during the summer season while minimum during the monsoon season. Among the planting densities, the higher soil temperature was recorded in lowest planting density and the lower soil temperature was recorded in high planting density at each depth level (5 cm, 10 cm and 20 cm depth).

The pruned stands had significantly higher soil temperature as compared to that of the unpruned stands during the post-monsoon season. No significant differences were found for pruning and planting density interactions.

7. Significant variation in relative water content was observed between planting densities in all seasons except the monsoon season. Relative water content estimates was generally maximum during the monsoon season while lowest during the summer season. The highest relative water content was associated with low planting density and the lowest relative water content was associated with high planting density. Relative water content was significantly higher in the pruned stands as compared to unpruned stands for the pre-monsoon and post-monsoon season but no variations were observed for the summer and monsoon seasons.

8. Canopy-air temperature difference (CATD) was maximum during the summer and lowest during the monsoon season. Among the planting densities, the CATD was significantly higher in high planting density and lower in low planting density during the summer and pre-monsoon seasons but it showed a statistically similar values for the monsoon and post monsoon seasons. Pruning had no effect on CATD during the study period. There was lack of significance for planting density and pruning interactions.

9. Evapotranspiration rate was higher during the summer season as compared to that of the other seasons. The evapotranspiration showed significant differences between planting densities in all seasons except the monsoon and post monsoon season. The highest evapotranspiration rate was found in low planting density and the lowest evapotranspiration rate was found in high planting density.

The evapotranspiration rate was significantly higher under the pruned stands as compared to the unpruned stands during the post-monsoon season but no variations were found for other seasons. No significant differences were found for pruning and planting density interactions during the study period.

10. The maximum PAR transmission was observed during the summer season and the lowest during the monsoon season. The open area showed significantly higher PAR value than *Acacia mangium* stand for all the seasons. The below canopy PAR was significantly higher in the low planting density and the lowest in high planting density at 5 m and 10 m above the ground level for all the seasons. Pruning had no significant effect on PAR during the study period. There was lack of significance between the planting density and pruning interactions. The diurnal variation of PAR showed an increasing trend from 9 am to 1pm with peak value corresponds to 1 pm and thereafter it followed declining trend. The average mid-day PAR transmittance from the unpruned stand (5000 trees/ha) to the pruned stand (625 trees/ha) canopies ranged from 24.27 % to 54.72 % of incident PAR above the canopy. The light extinction coefficient (K) for *Acacia mangium* stand was estimated to be 0.328.

11. The DBH of *Acacia mangium* was significantly increased with decreasing planting density. The DBH shows a variation from 0.137 m to 0.196 m as the density varied from higher to lower density classes. The DBH was not affected by the pruning treatments.

12. Mean tree height of *Acacia mangium* was significantly highest in relatively widely spaced stands and the lowest in high planting density. Pruning had no significant effect on tree height.

13. Aboveground standing biomass showed a decreasing trend with increasing stand density. The high planting density had the highest biomass accumulation while low planting density had the lowest biomass accumulation at individual tree level. On stand level basis, it showed reverse trend as it increased with increasing stand density.

14. Water use efficiency estimated by carbon isotope discrimination values shows no significant differences between planting densities and pruning treatments of *Acacia mangium* stand. Pruning and planting density interaction had no significant effect on water use efficiency.

15. Leaf area index (LAI) was considerably varied between planting densities and showed a variation from 1.46 in the pruned stand with 625 trees/ha to 2.45 in the unpruned stands with 5000 trees/ha. LAI was negatively correlated with air temperature (5 m and 10 m above the ground level), PAR (5 m and 10 m height above the ground level), soil temperature at various depth, relative water content, evapotranspiration and soil moisture (20 cm and 30 cm depth) while it was positively correlated with relative humidity at 5 m height above the ground level and soil moisture (5 cm and 10 cm depth). However, LAI did not show any correlation with CATD and relative humidity at 10 m height above the ground level.

16. Growth parameters had positive correlation with air temperature (5 m and 10 m above the ground level), PAR (5 m and 10 m above the ground level), soil temperature (5 cm, 10 cm and 20 cm depth), relative water content, evapotranspiration and soil moisture (5 cm and 10 cm depth) but it was negatively correlated with soil moisture (20 cm and 30 cm depth). However, it did not show any significant correlations with relative humidity and CATD.

17. Soil moisture content was positively correlated with relative humidity and relative water content. Whereas the evapotranspiration, CATD, air temperature, PAR and soil temperature was negatively correlated with the soil moisture content.

18. CATD had negative correlation with relative water content and soil moisture content while it showed positive correlation with evapotranspiration.

References

7. REFERENCES

Aasamaa, K. and Sober, A. 2011. Responses of stomatal conductance to simultaneous changes in two environmental factors. *Tree Physiol.* 31: 855–864.

Accieserin, H. and Ansin, O.E. 1994. Effect of tree density on light penetration and forage production in poplar (*Populus deltoides*). *Agroforestreria Enler Americal.* 1: 6-9.

Akers, M.K., Kane, M., Zhao, D.H., Teskey, R.O., and Daniels, R.F. 2013. Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations. *For. Ecol. Manag*. 310: 468-475.

Akhter, J., Mahmood, K., Tasneem, M.A., Malik, K.A., Naqvi, M.H., Hussain, F., and Serraj, R. 2005. Water-use efficiency and carbon isotope discrimination of *Acacia ampliceps* and *Eucalyptus camaldulensis* at different soil moisture regimes under semi-arid conditions. *Biol. Plant*. 49: 269–272.

Alcorn, P.J., Forrester, D.I., Smith, R.G.B., Thomas, D.S., James, R.N., Nicotra, A.B., and Bauhus, J. 2012. Crown structure and vertical foliage distribution in four year old plantation-grown *Eucalyptus pilularis* and *Eucalyptus cloeziana*. *Trees.* 24: 315-331.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. 1998. Crop evapotranspiration-guidelines for computing crop water Requirements. *Irrig. Drain*. Paper 56. Food and Agricultural Organization, Rome, Italy.

Anderson, P.D. and Tomlinson, P.T. 1998. Ontogeny affects response of northern red oak seedlings to elevated CO_2 and water stress. I. Carbon assimilation and biomass production. *New Phytol.* 140: 477-491.

Anthoni, P.M., Law, B.E., and Unsworth, M.H. 1999. Carbon and water vapour exchange of an open-canopied ponderosa pine ecosystem. *Agric. For. Meteorol.* 95: 151-168.

Aussenac, G. 2000. Interactions between forest stands and microclimate: ecophysiological aspects and consequences for silviculture. *Ann. For. Sci.* 57: 287–301.

Bacon, M.A. 2004. *Water use efficiency in plant biology*. Black House Publishers, Oxford, UK, pp. 78-89.

Baldocchi, D.D. and Collineau, S. 1994. The physical nature of solar radiation in heterogeneous canopies: spatial and temporal attributes. In: Caldwell, M.M. and Pearcy, R.W. (eds), *Exploitation of Environmental Heterogeneity by Plants: Ecophysiological Processes Above and Belowground*. Academic Press, San Diego, CA, pp. 21–72.

Beadle, C.1997. Dynamics of leaf and canopy development. In: Nambiar, E.Z. and Brown A.G. (eds), *Management of soil, nutrients and water in tropical plantation forests*. ICIAR, Canberra, pp. 169–212.

Begum, S.S., Nakaba, S., Oribe, Y., Kubo, T., and Funanda, R. 2007. Induction of cambial reactivation by localized heating in a deciduous hardwood hybrid poplar (*Populus sieboldii* X *P.grandidentata). An. Bot*. 44: 439-447.

Belsky, A.J., Amundson, R.G., Duxbury, J.M., Riha, S.J., Ali, A.R., and Mwonga, S.M. 1989. The effects of trees on their physical, chemical, and biological environments in a semi-arid savanna in Kenya. *J. Appl. Ecol.* 26: 1005–1024.

Benomar, L., DesRochers, A., and Larocque, G. 2011. Changes in specific leaf area and photosynthetic nitrogen-use efficiency associated with physiological acclimation of two hybrid poplar clones to intraclonal competition. *Can. J. For. Res.* 41: 1465–1476.

Bhimappa, K. 2014. Bamboo (*Dendrocalamus strictus* Roxb) based agroforestry systems: planting density effects on biomass accumulation, carbon sequestration, root distribution pattern and understorey crop productivity. Ph.D. (For) thesis, Kerala Agricultural University, Thrissur, 122 p.

Boffa, J.M., Taonda, S.J.B., Dickey, J.E., and Knudsen, D.M. 1999. Field-scale influence of karité (*Vitellaria paradoxa*) on white sorghum production in the Sudan zone of Burkina Faso, West Africa. *Agrofor. Syst*. 23: 415-422.

Bormann, B.T. and Gordon, J.C. 1984. Stand density effects in young red alder plantations: productivity, photosynthate partitioning, and nitrogen fixation. *Ecol.* 65: 394-402.

Breda, N., Granier, A., and Aussenac, G. 1994. Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea)* *Tree Physiol.* 15: 295-306.

Breda, N., Granier, A., and Aussenac, G. 1995. Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest (*Quercus petraea).* *Tree Physiol.* 15: 295–306.

Bredenkamp, B.V., Malan, F.S., and Conradie, W. E. 1980. Some effects of pruning on growth and timber quality of *Eucalyptus grandis* in Zululand. *S. Afr. For. J.* 114: 29–34.

Breshears, D.D., Rich, P.M., Barnes, F.J., and Campbell, K. 1997. Overstory imposed heterogeneity in solar radiation and soil moisture in a semiarid woodland. *Ecol. Appl.* 7: 1201–1215.

Brooks, J.R., Flanagan, L.B., Varney, G.T., and Ehleringer, J.R. 1997. Vertical gradients in photosynthetic gas exchange characteristics and refixation of respired CO_2 within boreal forest canopies. *Tree Physiol.* 17(1): 1-12.

Brown, M.J. and Parker, G.G. 1994. Canopy light transmittance in a chronosequence of mixed-species deciduous forest. Can. J. For. Res. 24: 1694–1703.

Buchmann, N., Brooks, J.R., Rapp, K.D., and Ehleringer, J.R. 1996. Carbon isotope composition of C_4 grasses is influenced by light and water supply. *Plant, Cell Environ*. 19(4): 392-402.

Buchmann, N., Kao, W.Y., and Ehleringer, J. 1997. Influence of stand structure on C_{13} of vegetation, soils, and canopy air within deciduous and evergreen forests in Utah, United States. *Oecologia*. 110: 109–119.

Bullard, M.J., Mustill, S.J., Carver, P., and Nixon, P.M.I. 2002. Yield improvements through modification of planting density and harvest frequency in short rotation coppice salix species in two morphologically diverse varieties. *Biomass Bioenerg*. 22: 27–33.

Caldwell, M., Meister, H., Tenhunen J., and Lange, O. 1986. Canopy structure, light microclimate and leaf gas exchange of *Quercus coccifera* L. in a Portuguese macchia: measurements in different canopy layers and simulations with a canopy model. *Trees.*1: 25–41.

Cameron, J. T. and Penna, I. W. 1988. *The Wood and the Trees*. Australian Conservation Foundation, Melbourne, pp. 143-154.

Cannel, M.G.R. 1983. Plant populations and yield of tree and herbaceous crops. In: Huxley, P.A. (ed.), *Plant research and Agroforestry*. ICRAF, Nairobi, pp. 455-502.

Caramori, P.H., Androcioli, A., and Leal, A.C. 1996. Coffee shade with *Mimosa scabrella* Benth for frost protection in southern Brazil. *Agrofor. Syst*. 33(3): 205–214.

Centritto, M., Magnani, F., Lee, H.S.J., and Jarvis, P.G. 1999. Interactive effects of elevated [CO_2] and drought on cherry (*Prunus avium*) seedlings. *New Phytol.* 141: 141-153.

Chamaillard, S., Fichot, R., Vincent-Barbaroux, C., Bastien, C., Depierreux, C., Dreyer, E., Villar, M., and Brignolas, F. 2011. Variations in bulk leaf carbon isotope discrimination, growth and related leaf traits among three *Populus nigra* L. populations. *Tree Physiol.* 31: 1076–1087.

Charreau, C. and Vidal, P. 1965. Influence de *I'Acacia albida* Del. sur lesol, nutrition minérale et les rendements des mils *Pennisetum* au Sénégal. *Agronomie Tropicale*. 20: 600–626.

Chen, J.Q., Franklin, J.F., and Spies, T.A. 1993. Contrasting microclimates among clear-cut, edge, and interior of old-growth Douglas-fir forest. *Agric. For. Meteorol.* 63: 219–237.

Chen, J.Q., Saunders, S.C., Crow, T.R., Naiman, R.J., Brosofske, K.D., Mroz, G.D., Brookshire, B.L., and Franklin, J.F. 1999. Microclimate in forest ecosystem and landscape ecology - Variations in local climate can be used to monitor and compare the effects of different management regimes. *BioSci.* 49: 288–297.

Chirko, C.P., Gold, M.A., and Jiang, J.P. 1999. Influence of direction and distance from trees on wheat yield and photosynthetic photon flux density in a Paulownia and wheat intercropping systems. *For. Ecol. Manag.* 83: 171–180.

Chris, S. P. 2001. The interaction between climate change, soil moisture stress and stand density in a red pine plantation. *ECO services International.* 35: 7-23.

Cinnerella, S., Farno, F., perniosa, G., and Tersoruosa, A.M. 1993. Effect of thinning on soil moisture content. *C. J. For. Res.* 24: 17-22.

Cole, E. and Newton, M. 1987. Fifth-year response of Douglas-fir to crowding and non-coniferous competition. *C. J. For. Res*. 17: 181-186.

Comstock and Ehleringer. 1993. Physiological and morphological responses to elevated CO_2 and a soil moisture deficit of temperate pasture species growing in an established plant community. *J. Exp. Bot*. 50: 233-242.

Dakin, A. J. 1982. Pruning trial with Sugi. *N. Z. J. For*. 27: 89–100.

Dancette, C. and Poulain, J.F. 1969. Influence of *Acacia albida* on pedoclimatic factors and crop yields. *Afr. Soils*. 14(1): 143–184.

DeBell, D.S. and Giordano, P.A. 1994. Growth Patterns of Red Alder. In: Hibbs, D.E., DeBell, D.S., and Tarrant, R.F. (Eds), *The Biology and Management of Red Alder, Corvallis*: Oregon, St. University Press, pp. 116-30.

DeBell, D.S., Clendenen, G.W., Harrington, C.A., and Zasada, J.C. 1996. Tree growth and stand development in short-rotation Populus plantings: seven year results for two clones at three spacings. *Biomass Bioenerg*. 11: 253–26.

Degen, A. and Berliner, P.R. 1997. Livestock and vegetal production in deserts using runoff water. Report No. CA 13-061, USAID/CAR.

Delacruz, L.U. and Luna, A.C. 1994. Effects of *Acacia auriculiformis* and *Gmelina arborea* on soil and microclimate of a degraded grassland in Philippines. *For. Ecol. Manag*. **1:** 46–54.

Deng, Q., Zhou, G., Liu, J., Liu, S., Duan, H., and Zhang, D. 2010. Responses of soil respiration to elevated carbon dioxide and nitrogen addition in young subtropical forest ecosystems in China. *Biogeosciences*. 7: 315–328.

Depommier, D. 1996. Structure, dynamique et fonctionnement des parcs à *Faidherbia albida* (Del.) A. Chev. Caractérisation et incidence des facteurs biophysiques et anthropiques sur I'aménagement et le devenir des parcs de Dossi et de Watinoma, Burkina Faso. Ph.D. thesis, Université Pierre et Marie Curie, Paris, 86p.

Dewar, R.C. 1996. The correlation between plant growth and intercepted radiation: an interpretation in terms of optimal plant nitrogen content. *An. Bot*. 78: 125-136.

Diakite, T. 1995. Concurrence pour l'eau et les éléments nutritifs du sol entre ligneux et cultures. Le karité et le sorgho en zone semi-aride au Mali. Mémoire. M.Sc. thesis, Université, Laval, Canada, 69p.

Doran, J.C. and Turnbull, J.W. 1997. Australian trees and shrubs: species for land rehabilitation and farm planting in the tropics. ACIAR Monograph 24, Australian Centre for International Agricultural Research, Canberra, Australia.

Douglas, G.B., Walcroft, A.S., Hurst, S.E., Potter, J.F., Foote, A.G., Fung, L., Edwards, W.R.N., and Dijssel, C. 2006. Interactions between widely spaced young poplars (Populus spp.) and introduced pasture mixtures. *Agrofor. Syst*. 66: 165–178.

Droppelmann, K., Ephrath, J.E., and Berlinear, P. 2000. Tree/crop complementary in an arid zone runoff agroforestry system in northern Kenya. *Agrofor. Syst*. 49: 223–243.

Eastham, J. and Rose, C. W. 1988. Pasture evaporation under varying tree planting density in an agroforestry experiment. *Agric. Water Manag*. 15(1): 87-105.

Eastham, J., Rose, C.W., Charles-Edwards, D.A., Cameron, D.M., and Rance, S.J. 1990. Planting density effects on water use efficiency of trees and pasture in an agroforestry experiment. *N. Z. J. For. Sci*. 20: 39–53.

Egli, P., Maurer, S., Gunthardt-Goerg, M.S., and Korner, C. 1998. Effects of elevated CO_2 and soil quality on leaf gas exchange and aboveground growth in beech-spruce model ecosystems. *New Phytol.* 140: 185-196.

Ehleringer, J.R. and Cooper, T.A. 1986. Correlation between carbon isotope ratio and micro habitat in desert plants. *Oecologia.* 76: 562–566.

Facelli, J.M. and Pickett, S.T.A. 1991. Plant litter: Its dynamics and effects on plant community structure. *Bot. Rev*. 57: 1–32.

Farquhar, G.D. and Richards, R.A. 1984. Isotope composition of plant carbon correlates with water-use efficiency of wheat genoptype. *Aust. J. Plant Physiol.* 11: 539–552.

Farquhar, G.D., Ball, M.C., Von Caemmerer, S., and Roksaadic, Z. 1982. Effects of salinity and humidity on δ13C value of halophytes-evidence for diffusional isotope fractionation determined by the ratio of intercellular/atmospheric partial pressure of CO_2 under different conditions. *Oecologia*. 52: 121–124.

Farquhar, G.D., Ehleringer, J.R., and Hubick, C.T. 1989. Carbon isotope discrimination and photosynthesis. *Ann. Rev. Plant Physiol.* 40: 503–537.

Fassnacht, K.S. and Gower, S.T. 1997. Interrelationships among the edaphic and stand characteristics, leaf area index, and aboveground net primary production of upland forest ecosystems in north central Wisconsin. *Can. J. For. Res.* 27: 1058-1067.

Feddema, J.J. and Freire, S. 2001. Soil degradation, global warming and climate impacts. *Clim. Res.* 17: 209–216.

Ferranti, L. and Viterbo, P. 2006. The European summer of 2003: sensitivity to soil water initial conditions. *J. Clim*. 19: 3659–3680.

Fischer, E.M., Seneviratne, S.I., Vidale, P.L., Luthi, D., and Schar, C. 2007. Soil moisture - atmosphere interactions during the 2003 European summer heat wave. *J. Clim*. 20: 5081–5099.

Forrester, D.I., Collopy, J.J., Beadle, C.L., Warren, C.R., and Baker, T.G. 2012. Effect of thinning, pruning and nitrogen fertiliser application on transpiration, photosynthesis and water use efficiency in a young *Eucalyptus nitens* plantation. *For. Ecol. Manag*. 266: 286–300.

Forrester, D.I., Theiveyanathan, S., Collopy, J.J., and Marcar, N.E. 2010. Enhanced water use efficiency in a mixed *Eucalyptus globulus* and *Acacia mearnsii* plantation. *For. Ecol. Manag*. 259: 1761–1770.

Forrester, J.J., Collopy, C.L., Beadle, T.G., and Baker, T.G. 2013. Interactive effects of simultaneously applied thinning, pruning and fertiliser application treatments on growth, biomass production and crown architecture in a young *Eucalyptus nitens* plantation. *For. Ecol. Manag*. 267: 104–116.

Gao, L., Shi, B., Tang, C.S., Wang, B.J., and Gu, K. 2010. Experimental study of temperature effect on FDR measured soil volumetric water content. *J. Glac. Geoc*. 32(5): 964–969.

Garcia, R.L., Long, S.P., Wall, G.W., Osborne, C.P., Kimball, B.A., Nie, G.Y., Pinter Jr., P.J., Lamorte, R.L., and Wechsung, F. 1998. Photosynthesis and conductance of spring-wheat leaves: field response to continuous free-air atmospheric CO_2 enrichment. *Plant, Cell and Envi*. 21: 659-669.

Gardner, B.R., Blad, B.L., and Watts, D.G. 1981. Plant and air temperature in differentially-irrigated corn. *Agric. meterol*. 25: 207-217.

Garratt, J.R. 1992. *The Atmospheric Boundary Layer*. Cambridge University Press, Cambridge, UK.

Geiger, R., Aron, R.H., and Todhunter, P. 2003. *The Climate near the ground*. Rowman and Littlefield Publishers, Lanham, Maryland.

Ghosh, R. C. and Dabral, B. C. 1980. Water relations of *Pinus caribaea* in high density stocking in juvenile stage. *Indian For.* 106(9): 587-595.

Gilbert, I.R., Seavers, G.P., Jarvis, P.G., and Smith, H. 1995. Photomorphogenesis and canopy dynamics. Phytochrome-mediated proximity perception accounts for the growth dynamics of canopies of *Populus trichocarpa* x *P. deltoides*. *Plant, Cell and Envi.* 18: 475-497.

Grace, J. C., Jarvis, P. G., and Norman, J. M. 1987. Modelling the interception of solar radiant energy in intensively managed stands. *N. Z. J. For. Sci.* 17(2): 193-209.

Green, D.S., Kruger, E.L., Stanosz, G.R., and Isebrands, J.G. 2001. Light-use efficiency of native and hybrid poplar genotypes at high levels of intracanopy competition. *Can. J. For. Res.* 31: 1030–1037.

Green, F.H.W., Harding, R.J., and Oliver, H.R. 1984. The relationship of soil temperature to vegetation height. *J. Clim*. 14: 229–240.

Green, S.R., Grace, J., and Hutchings, N.J. 1995. Observations of turbulent air flow in three stands of widely spaced Sitka spruce. *Agric. For. Meteorol.* 74: 205-225.

Groot, A. and Carlson, D.W. 1996. Influence of shelter on night temperatures, frost damage, and bud break of white spruce seedlings. *Can. J. For. Res.* 26: 1531–1538.

Guerfel, M., Oun, Y., Boujnah, D., and Zarrauk, M. 2010. Effect of planting density on water relations and production of "chermali" olive trees (*Olea eueopaea L.). Trees.* 24: 1137-1142.

Guttormsen, G. 1974. Effects of root medium and watering on transpiration, growth and development of glasshouse crops. II. The relationship between evaporation pan measurements and transpiration in glasshouse crops. *Plant Soil.* 40(3): 461–478.

Hall, D.O. and Scurlock, J.M.O. 1993. *Photosynthesis and Production in a Changing Environment*. Chapman and Hall, New York, 58p.

Handa, A.K., Rai, P., Ram, M., Ajithkumar, R.V., Chauhan, S.P.S., and Ram, B. 2007. Effect of pruning intensity on growth and productivity of MPTs and crop under rainfed conditions. *Rangel. Manag. Agrofor.* 28(2): 985-989.

Harper, J.L. and White, J. 1974. The demography of plants. *An. Rev. Ecol. Sys.* 5: 419–463.

Harrington, T.B., Pabst, R.J., and Tappeiner, J.C. 1994. Seasonal physiology of Douglas-fir saplings: response to microclimate in stands of tanoak or Pacific madrone. *For. Sci.* 40(1): 59-82.

Heithecker, T.D. and Halpern, C.B. 2006. Variation in microclimate associated with dispersed-retention harvests in coniferous forests of western Washington. *For. Ecol. Manag.* 226: 60–71.

Helmers, A. E. 1948. *Early results from thinning seed spots*. Research Note No. 48. Missoula, MT: U.S. Department of Agriculture and Forest service, Northern rocky mountain forest and Range experiment station, United States of America, 5p.

Hingston, F.J., Galbraith, J.H., and Dimmock, G.M. 1994. *Evaluating the effect of soils and climate on productivity of Eucalyptus globulus plantations on contrasting sites in south west of Western Australia*. Rural Industries Research and Development Corporation Final Report No. 41, Australia, 52p.

Hirschi, M., Seneviratne, S.I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O.B., Formayer, H., Orlowsky, B., and Stepanek, P. 2011. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geosciences.* 4: 17–21.

Huber, A. and Trecaman, R. 2002. The effect of the inter-annual variability of rainfall on the development of *Pinus radiata* (D. Don) plantations in the sandy soil zones of VIII region of Chile. *Bosque*. 23(2): 43-49.

Husband, G. Kimball. B.A., Pinter, P.J., Jr., Wall, G.W., LaMorte, R.L., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D., and Brooks, T.J. 2004. CO_2 enrichment and soil nitrogen effects on wheat evapotranspiration and water use efficiency. *Agric. For. Meteorol.* 104: 85-105.

Jackson, N.A., Wallace, J.S., and Ong, C.K. 2000. Tree pruning as means of controlling water use in an agroforestry systems in Kenya. *For. Ecol. Manag*. 126(2): 133-148.

Jackson, R.D. 1982. Canopy temperature and crop water stress. *Adv. Irr.* 1: 43-85.

Jacobs, A.F.G., Heusinkveld, B.G., and Holtslag, A.A.M. 2011. Long-term record and analysis of soil temperatures and soil heat fluxes in a grassland area, the Netherlands. *Agric. For. Meteorol.* 151: 774–780.

Jaeger, E. and Seneviratne, S. 2011. Impact of soil moisture–atmosphere coupling on European climate extremes and trends in a regional climate model. *Clim. Dyn*. 36: 1919–1939.

Jahnke, L.S. and Lawrence, D.B. 1965. Influence of photosynthetic crown structure on potential productivity of vegetation, based primarily on mathematical models. *Ecol.* 46: 319-326.

Jarvis, P.G. and McNaughton, K.G. 1986. Stomatal control of transpiration: Scaling up from leaf to region. *Adv. Ecol. Res. 15*: 1–49.

Jimenez, C., Tejedor, M., and Rodriguez, M. 2007. Influence of land use changes on the soil temperature regime of Andosols on Tenerife, Canary Islands and Spain. *Eur. J. Soil Sci.* 58: 445–449.

Jirasuktaveekul, W., Witthawatchutikul, P., and Suksawang, S. 1992. Soil moisture under eucalyptus plantations and abandoned areas at Ban huang ma fuang, Rayong province. *For. Ecol. Manag*. 2(8): 56-66.

Johnson, K. 1995. *Agroforestry in dry savanna areas in Africa: Interactions between trees, soils and crops*. Ph.D. thesis, Swedish University of Agricultural Sciences, Umea, Sweden.

Karani, P. K. 1978. Pruning and thinning in a *Pinus patula* stand at Lendu plantation, Uganda. *Commw. For. Rev*. 57: 269–278.

Keenan, T.F., Hollinger, D.Y., Bohrer, G., and Richardson, A.D. 2013. Increases in water use efficiency as atmosphere carbon dioxide concentration rise. *Nature*. 499: 324-328.

Kinama, J. M., Stigter, C. J., Ong, C. K., Nganga, J. K., and Gichuki, F. N. 2005. Evaporation from soils below sparse crops in contour hedgerow agroforestry in semi-arid Kenya. *Agric. For. Meterol*. 130: 149-162.

Knowe, S.A. and Hibbs D.E. 1996. Stand structure of young red alder as affected by planting density. *For. Ecol. Manag*. 82: 69-85.

Koech, E. K. and Whitbread, R. 2000. Disease incidence and severity on beans in alleys between *Leucaena* hedgerows in Kenya. *Agrofor. syst*. 49: 85-101.

Kramer, J.P. and Boyer, J.S. 1995. *Water Relations of Plants and Soils*. Academic Press, San Diego, CA, 59 p.

Kumar, B. M., George, S. J., and Suresh, T. K. 2000. Productivity of forage grasses grown in association with fast growing multipurpose tree and assessment of post-rotation soil fertility in the humid tropics of peninsular India. *Agrofor. Syst*. 46: 131-146.

Kumar, B. M., Thomas, J. and Fisher, R. F. 2001. *Ailanthus triphysa* at different density and fertilizer levels in Kerala, India: Tree growth, light transmittance and understory ginger yield. *Agrofor. Syst*. 52(2): 133:134.

Kunhamu, T. K., Kumar, B. M., Viswanath, S., and Sureshkumar, P. 2008. Thinning promotes understorey ginger productivity in *Acacia mangium* Willd. stands of Kerala, India. *Proceeding of the International Agroforestry Conference*. Kuala Lumpur, Malaysia, 1 to 2 August 2006. Yahya, A.Z., Ngah, M.L., Md. Ariff, F.F., Rahman, Z.A., Abdullah, M.Z., Philip, E., and Chik S.W. (eds), Trans. of the Malaysian Society of Plant Physiology, Forest Research Institute, Malaysia. 15: 47-60.

Kunhamu, T.K. 2006. Stand density manipulation and pruning of *Acacia mangium* Willd to optimize productivity in an agrisilvicultural system. Ph.D. thesis, Institute of Forest Genetics and Tree Breeding, Coimbatore, 187p.

Kunhamu, T.K., Kumar, B.M., and Vishwanath, S. 2005. Tree allometry, volume and aboveground biomass yield in a seven year old *Acacia mangium* Willd. stand at Thiruvizhamkunnu, India. In: Tewari, V.P. and Srivastava, R.L. (eds), *Multipurpose trees in the Tropics: Management and Improvement Strategies*. Proceedings of the international symposium. Multipurpose trees in the tropics: assessment, growth and management. Scientific Publishers, Jodhpur, pp. 415–442.

Kupper, P., Sober, J., Sellin, A., Lohmus, K., Tullus, A., Räim, O., Lubenets, K., Tulva, I., Uri, V., Zobel, M., Kull, O., and Sober, A. 2011. An experimental facility for free air humidity manipulation (FAHM) can alter water flux through deciduous tree canopy. *Environ. Exp. Bot*. 72: 432–438.

Kuppers, M. 1994. Carbon relations and competition between woody species in central European hedgerow III. Carbon and water balance on the leaf level. *Oecologia*. 65: 94-100.

Kuuluvainen, T. and Pukkula, T. 1987. Effect of crown shape and tree distribution on the spatial distribution of shade. *Agric. For. Meteorol.* 40: 215-231.

Ladjal, M., Deloche, N., Huc, R., and Ducrey, M. 2007. Effects of soil and air drought on growth, plant water status and leaf gas exchange in three Mediterranean cedar species: *Cedrus atlantica, C. brevifolia and C. libani*. *Trees Struct. Funct.* 21: 201–213.

Landsberg, J.J. and Gower, S.T. 1997. *Applications of physiological ecology of forest management*. Academic Press, San Diego, CA.

Landsberg, J.J. and Sands, P.J. 2011. *Physiological Ecology of Forest Production: Principles, Processes and Modelling*. Elsevier Inc, Oxford, UK.

Lanner, R. M. 1985. On the insensitivity of height growth to spacing. *For. Ecol. Manag.* 13: 143-148.

Law, B.E., Cescatti, A., and Baldocchi, D.D. 2001. Leaf area distribution and radiative transfer in open-canopy forests: implications for mass and energy exchange. *Tree Physiol.* 21: 777–787.

LeCain, D.R. and Morgan, J.A. 1998. Growth, gas exchange, leaf nitrogen and carbohydrate concentrations in NADP-ME and NADP-ME C_4 grasses grown in elevated CO_2. *Physiologia Plant.* 102: 297-306.

Lendzion, J. and Leuschner, C. 2008. Growth of European beech (*Fagus sylvatica* L.) saplings is limited by elevated atmospheric vapour pressure deficits. *For. Ecol. Manag.* 256: 648–655.

Leuschner, C. 2002. Air humidity as an ecological factor for woodland herbs: leaf water status, nutrient uptake, leaf anatomy, and productivity of eight species grown at low or high vapour pressure deficit levels. *Flora – Morphol. Distribution, Funct. Ecol. Plants.* 197: 262–274.

Leymarie, J., Lasceve, G., and Vavasseur, A. 1999. Elevated CO2 enhances stomatal responses to osmotic stress and abscisic acid in *Arabidopsis thaliana*. *Plant, Cell Environ.* 22: 301-308.

Li, J.G., Huang, X.M., Huang, H.B., Qui DongLiang, Mitra, S.K., and Diczbalis, Y. 2010. An overview of factors related to fruit size in *Litchi chinensis* Sonn. ***Acta Hortic***. 13: 477-482.

Li, M.X., Du, S.N., Bai, G.S., and Geng G.J. 2012. Effects of renewal pruning on soil moisture and growth of apple tree. *Agric. Life Sci.* 38(4): 467-476.

Liu, S. Cohen, J. Tanny, J.H., and Lemcoff, G. 2008. Huang Estimation of banana (*Musa* sp.) plant transpiration using a standard 20 cm pan in a greenhouse. *Irrig. Drain. Syst*. 22(3): 311–323.

Lloyd, J. and Taylor, J.A. 1994. On the temperature dependence of soil respiration. *Funct. Ecol.* 8: 315–323.

Luckhoff, H. A. 1949. The effect of live pruning on the growth of *Pinus patula, P. caribaea* and *P. taeda*. *S. Afr. For.* 18: 25–55.

Ma, S.Y., Concilio, A., Oakley, B., North, M., and Chen, J.Q. 2010. Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments. *For. Ecol. Manag.* 259: 904–915.

Maier-Maercker, U. 1998. Dynamics of change in stomatal response and water status of Picea abies during a persistent drought period: a contribution to the traditional view of plant water relations. *Tree Physiol.* 18: 211–222.

Majid, N.M. and Paudyal, B.K. 1992. Pruning trial for Acacia mangium Willd. Plantation in Peninsular Malaysia. *For. Ecol. Manage.* 47: 285-293.

Mann, J.E., Curry, G.L. and Sharp, P.J.H. 1979. Light interception by isolated plants. *Agric. Meteorol.* 20: 205-221.

Marshall, T. J. and Holmes, J. W. 1988. *Soil Physics* (2^{nd} Ed.). Cambridge University Press, Cambridge, 374p.

Martin, B. and Thorstenson, Y.R. 1988. Stable carbon isotope composition (δ13C), water use efficiency, and biomass productivity of *Lycopersicon esculentuni, Lycopersicon pennellti,* and the F1 hybrid. *Plant Physiol.* 88: 213–217.

Martin-Benito, D., Del Rio, M., Heinrich, I., Helle, G., and Canellas, I. 2010. Response of climate-growth relationships and water use efficiency to thinning in a *Pinus nigra* afforestation. *For. Ecol. Manag*. 259: 967–975.

Martius, C., Höfer, H., Garcia, M.V.B., Römbke, J., Förster, B., and Hanagarth, W. 2004. Microclimate in agroforestry systems in central Amazonia: does canopy closure matter to soil organisms? *Agr. Syst*. **60**: 291–304.

Mathew, T., Kumar, B. M., Babu, K.V.S., and Umamaheshwaran. 1992. Comparative performance of four multipurpose trees associated with four grass species in the humid regions of south India. *Agrofor. Syst*. 17: 205-218.

McDowell, N., Brooks, J.R., Fitzgerald, S.A., and Bond, B.J. 2003. Carbon isotope discrimination and growth response of old *Pinus ponderosa* trees to stand density reductions. *Plant, Cell Environ.* 26: 631–644.

McJannet, D. and Vertessy, R. 2001. Effects of thinning on wood production, leaf area index, transpiration and canopy interception of a plantation subject to drought. *Tree Physiol. 21*: 1001–1008.

Mead, D.J. and Speechly, H.T. 1991. Growing Acacia mangium for high quality sawlogs in Peninsular Malaysia. In: Sheikh, A. (Ed.), *Recent Developments in Tree Plantations of Humid/Sub-Humid Tropics of Asia*. Universiti Pertanian Malaysia, Serdang, pp. 54–69.

Medhurst, C.L. and Beadle. 2005. Photosynthetic capacity and foliar nitrogen distribution in *Eucalyptus nitens* is altered by high-intensity thinning. *Tree Physiol.* 25: 981–991.

Medhurst, J.L., Battaglia, M., and Beadle, C.L. 2002. Measured and predicted changes in tree and stand water use following high-intensity thinning of an 8-year-old *Eucalyptus nitens* plantation. *Tree Physiol.* 22: 775–784.

Mellander, P.E., Bishop, K., and Lundmark, T. 2004. The influence of soil temperature on transpiration: a plot scale manipulation in a young Scots pine stand. *For. Ecol. Manag.* 195: 15–28.

Mitscherlich, G. 1981. Microclimatic aspects in plantations of coffee (*Coffea arabica* L.) planted at high density.1996. In: *Simpósio Internacional sobre Cafe Adensado,* 28- 31 march 1996, Londrina, Brazil, pp. 45-69.

Monteith, J.L. and Unsworth, M.H. 1990. Crop Micrcometerology (i) Profiles and fluxes. In: *Principles of Environmental Physics*, Chapman & Hall, New York, pp. 231-244.

Morales, P. and Davies, F.S. 2002. Pruning and skirting effects on canopy microclimate, growth and flowering of ‘ORLANDO’ tangelo trees. *Proc. fla. State hort. soc.* 115: 22-26.

Morecroft, M.D., Taylor, M.E., and Oliver, H.R. 1998. Air and soil microclimates of deciduous woodland compared to an open site. *Agri. For. Meteorol.* 90: 141–156.

Moussa, H. 1997. Germination du palmier doum (*Hyphaene thebaica* Mart.) et analyse de son interaction avec le mil (*Pennisetum glaucum* L.) en zone semi-aride du Niger. Ph.D. thesis, Université Lava, Québec, Canada.

National Research Council. 1983. *Mangium and other fast growing acacias for the humid tropics*. National Academic Press, Washington, DC, 59p.

Newaj, R., Dar, S.A., and Bhargava, M.K. 2007. Microclimatic changes in *Albizia procera* based agrisilvicultural system. In: *National Symposium "Rangeland and forage resources in changing socio-economic scenario"*, 15-17 November 2007, India.

Ngegba, M., Mugasha, A.G., and Chamshama, S.A.O. 2001. Effect of forest plantation on select soil properties at SAO hill forest plantations, Iringa, Tanzia. *J. Trop. for. Sci.* 13(3): 477-488.

Ngugi, M.R., Hunt .M.A., Doley, D., Ryan, P., and Dart P.J. 2003. Effect of soil water availability on water use efficiency of *Eucalyptus cloeziana* and *E. argophloia* plants. *Aus. J. Bot*. 51: 159-166.

Nizinski, J. and Grouzis, M. 1991. Bilan hydrique d'une steppe à Acacia tortilis spp. raddiana et Balanites aegyptiaca au nord du Sénégal. In: *IV Congrès International des Terres de Parcours, Association Française de Pastoralisme*, 22–26 April 1991, Montpellier. CIRAD, France, pp. 285–288.

Norisada, M., Hitsuma, G., Kuroda, K., Yamanoshita, T., Masumori, M., Tange, T., Yagi, I., Nuyum, T., Sasaki, S., and Kojima, K. 2005. *Acacia mangium*, a nurse tree candidate for reforestation on degraded sandy soils in the Malay Peninsula. *For. Sci.* 51: 498–510.

Ogle, K., Lucas, R.W., Bentley, L.P., Cable, J.M., Barron-Gafford, G.A., and Griffith, A. 2012. Differential daytime and night-time stomatal behaviour in plants from North American deserts. *New Phytol.* 194: 464–476.

Oker-Blom, P. and Kellomlki, S. 1988. Effect of angular distribution of foliage on light absorption and photosynthesis in the plant canopy: theoretical computation. *Agric. Meteorol.* 26: 105-l16.

Ong, D.K. and Monteith, J.L. 2007. Response of pearl millet to light and temperature. *Field Crops Res.* 11: 141–160.

Oribe. Y., Funada, R., Shibayaki, M., and Kubo, T. 2001. Cambial reactivation in locally heated stems of the evergreen conifer *Abies sachalinensis* (schimth) Masters. *Planta*. 212: 684-691.

Ovaska, J., Walls, M., and Mutikainen, P. 1992. Changes in leaf gas exchange properties of cloned *Betula pendula* saplings after partial defoliation. *J. Exp. Bot*. 43: 1301–1307.

Papadopoulos, D.P. and Ormrod. 1988. Plant spacing effects on light interception by greenhouse tomatoes. *Can. J. Plant Sci.* 68(4): 1197–1208.

Parrotta, J. 1992. The role of plantation forests in rehabilitating degraded tropical ecosystems. *Agric. Ecosyst. Environ*. 41(2): 115-133.

Peck, J.E., Zenner, E.K., and Palik, B. 2012. Variation in microclimate and early growth of planted pines under dispersed and aggregated overstorey retention in mature managed red pine in minnesota. *C. J. For. Res*. 42: 279–290.

Pepin, S., Livingston, N.J., and Whitehead, D. 2002. Responses of transpiration and photosynthesis to reversible changes in photosynthetic foliage area in western red cedar (*Thuja plicata*) seedlings. *Tree Physiol. 22*: 363–371.

Pereira, H. C. 1959. *Soil moisture effects of crop-spacing and of shade trees in a Limuru tea garden*: A Progress Report Circular No. 6, Tea Research Institute of East Africa, pp. 4-9.

Pinkard, E.A. 2003. Physiological and growth responses related to pattern and severity of green pruning in young *Eucalyptus globulus*. *For. Ecol. Manag. 182*: 231–245.

Pinkard, E.A. and Beadle, C.L. 1998. Regulation of photosynthesis in *Eucalyptus nitens* (Deane and Maiden) Maiden following green pruning. *Trees Struct. Funct*. 12: 366–376.

Pinkard, E.A., Beadle, C.L., Davidson, N.J., and Battaglia, M. 2004. Photosynthetic responses of *Eucalyptus nitens* (Deane and Maiden) Maiden to green pruning. *Tree Struct. Funct. 12*: 119–129.

Porte, A., Huard, F., and Dreyfus, P. 2004. Microclimate beneath pine plantation, semi-mature pine plantation and mixed broadleaved-pine forest. *Agric. For. Meterol.* 126: 175–182.

Pratap. B., Sharma, H.C., Goswami, A.M., Singh, S. K., and Mishra, L.N. 2003. Effects of pruning on photosynthetic rate, canopy microclimate and yield of mango cv. amrapali under high-density planting. *Indian J. Hortic.* 60: 339-342.

Quentin, A.G., O'Grady, A.P., Beadle, C.L., Mohammed, C., and Pinkard, E.A. 2012. Interactive effects of water supply and defoliation on photosynthesis, plant water status and growth of *Eucalyptus globulus*. *Tree Physiol.* 32: 958–967.

Quentin, A.G., O'Grady, A.P., Beadle, C.L., Pinkard, E.L., Worldege, D**.** 2011. Responses of transpiration and canopy conductance to partial defoliation of *Eucalyptus globulus* trees. *Agric. For. Meteorol.* 151: 356–364.

Querejeta, J.I., Barbera, G.G., Granados, A., and Castillo, V.M. 2008. Afforestation method affects the isotopic composition of planted *Pinus alepensis* in a semiarid region of Spain. *For. Ecol. Manag.* 254: 56–64.

Raich, J. and Tufekciogul, A. 2000. Vegetation and soil respiration: correlations and controls. *Biogeochemistry.* 48: 71–90.

Rakesh, K. 2009. Influence of planting density on growth and soil properties of 17 year old *Ailanthus triphysa* (Dennt.) Alston stand. B.Sc. dissertation, Kerala Agricultural University, Vellanikkara, Thrissur, India. 81 p.

Raupach, M.R., Finnigan, J.J., and Brunet, Y. 1996. Coherent eddies and turbulence in vegetation canopies: the mixing layer analogy. *Boundary Layer Meteorol.* 78: 351–382.

Renaud, V., Innes, J.L., Dobbertin, M., and Rebetez, M. 2011. Comparison between open-site and below-canopy climatic conditions in Switzerland for different types of forests over 10 years (1998-2007). *Theor. Appl. Clim*. 105: 119–127.

Rey, A. and Jarvis, P.G. 1998. Long-Term photosynthetic acclimation to increased atmospheric CO_2 concentration in young birch (*Betula pendula*) trees. *Tree Physiol.* 18: 441-450.

Rey, J. S. 1999. Effects of severe soil moisture deficit at specific growth stage of corn. *J. Agron.* 45: 618-625.

Rhoades, C. 1995. Seasonal pattern of nitrogen mineralization and soil moisture beneath *Acacia albida* (syn. *Faidherbia albida*) in central Malawi. *Agrofor. Syst*. 29(2): 133–145.

Ritchie, G.A. 1997. Evidence for red: far red signaling and photomorphogenic response in Douglas-fir (*Pseudotsuga menziesii*) seedlings. *Tree Physiol.* 17: 161-168.

Roberntz, P. and Stockfors, J. 1998. Effects of elevated CO_2 concentration and nutrition on net photosynthesis, stomatal conductance and needle respiration of field-grown Norway spruce trees. *Tree Physiol.* 18: 233-241.

Rodríguez-Calcerrada, J., Mutke, S., Alonso, J., Gil, L., Pardos, J.A., and Aranda, I. 2008. Influence of overstorey density on understory light, soil moisture and survival of two under planted oak species in a Mediterranean montane Scots pine forest. *For. Ecol. Manag.* 17(1): 31-38.

Rolim, G.S., Souza, P.S., Pedro, M.J., Gallo, P.B., and Pezzopane, J.R.M. 2008. Air temperature of coffee canopy before and after different types of pruning in Mococa SP, Brazil. In: *Proccedings of* ***International Conference on Coffee Science*****, 14-19 September 2008**, **Campinas, SP, Brazil,** pp.1254-1256.

Rossi, S., Deslauriers, A., Aufodillo, T., and Carrer, M. 2008. Critical temperature for xylogenesisin conifer of cold climate. *Glob. Ecol .Biogeogr.* 17: 696-707.

Runion, G.B., Mitchell, R.J., Green, T.H., Prior, S.A., Rogers, H.H., and Gjerstad, D.H. 1999. Longleaf pine photosynthetic response to soil resource availability and elevated atmospheric carbon dioxide. *J. Environ. Qual.* 28: 880-887.

Ryan, M.G., Linder, S., Vose, J.M., and Hubbard, R.M. 1994. Dark respiration in pines. *Ecol. Bull.* 43: 50-61.

Saifuddin, M., Hossain A.B.M., Normaniza, O., Osman, N., Sattar, M.A., Moneruzzaman, K.M., and Jahirul, M.I. 2010. Pruning impacts on shoot-root-growth, biochemical and physiological changes of *Bougainvillea glabra. Asian J. crop sci.* 4(7): 530-537.

Saini B.C., Misra K.K., and Singh R.V. 1997. Performance of wheat in intercropping system with Gutel (*Trewia nudiflora*) under shallow water table conditions. *An. Agric. Res.* 18: 51–55.

Sauerhaft, B. C., Thurow, T., and Berliner, P. 1999. Spacing and green manure effects on biomass yield in an arid land water catchment agroforestry system People and rangelands: building the future. In: *Proceedings of the VI International Rangeland Congress*, 19-23 July, 1999, Townsville, Queensland, Australia.

Saxe, H., Ellsworth, D.S., and Heath, J. 1998. Tree and forest functioning in an enriched CO_2 atmosphere. *New Phytol.* 139: 395-436.

Scharenbroch, B.C. and Bockheim, J.G. 2007. Impacts of forest gaps on soil properties and processes in old growth northern hardwood-hemlock forests. *Plant and Soil.* 294: 219–233.

Scull, P. 2007. Changes in soil temperature associated with reforestation in central New York State. *Phys. Geogr.* 28: 360–373.

Seneviratne, S.I., Luthi, D., Litschi, M., and Schar, C. 2006. Land-atmosphere coupling and climate change in Europe. *Nature.* 443: 205–209.

Seneweera, S.P., Ghannoum, O., and Conroy, J. 1998. High vapour pressure deficit and low soil water availability enhance shoot growth responses of a C_4 grass (*Panicum coloratum* cv. Bambatsi) to CO_2 enrichment. *Aust. J. Plant Physiol.* 25: 287-292.

Serraj, R., Allen, L.H., and Sinclair, T.R. 1999. Soybean leaf growth and gas exchange response to drought under carbon dioxide enrichment. *Glob. Change Biol.* 5: 283-291.

Sgherri, C.L.M., Quartacci, M.F., Menconi, M., Raschi, A., and Navari, F. 1998. Interactions between drought and elevated CO_2 on alfalfa plants. *J. Plant Physiol.* 152: 118-124.

Shangwei, S., WeiLun, Y., XinLi, X., XiaoDong, L., and SenKun, C. 2009. Effects of different pruning intensity on microclimate growth and yield of crops in agroforestry system. *J. Beijing For. Univ*. 31(1): 25-30.

Sharma, R.R. and Roomsingh. 2006. Pruning intensity modifies canopy microclimate, and influences sex ratio, malformation incidence and development of fruited panicles in 'Amrapali' mango (*Mangifera indica* L). *Scientia Hortic.* 109(2): 118-122.

Shashua-Bar, L. and Hoffman, M.E. 2000. Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. *Energy Build.* 31: 221–235.

Sibbald, A.R., Maxwell, T.J., Griffiths, J.H., Hutchings, N.J., Taylor, C.M., Tabbush, P.M., and White, I.M.S. 1992. Agroforestry research in the hills and uplands. In**:** ***ITE Symposium,*** **Institute of Terrestrial Ecology, United Kingdom**, pp. 74-77.

Singh, S.K., Sharma, R.R., and Manish, S. 2009. Effect of pruning on morpho-physiological parameters and microclimate under high density planting of mango (*Mangifera indica*). *Indian J. Agric. Sci.* 79(8): 632-635.

Sinoquet, H. and Bonhomme, R. 1995. Modeling radiative transfer in mixed and row intercropping systems. *Agric. For. Meteorol.* 62: 219–240.

Skariah, S. S. 2008. Effect of planting density and pruning on tree growth and soil characteristics in six year old *Acacia mangium* Stand. B.Sc. dissertation, Kerala Agricultural University, Vellanikkara, Thrissur, India. 84p.

Slatyer, R.O. 1967. *Plant-water relationships*. Academic Press, London, 366p.

Smart, D.R., Ritchie, K., Bloom, A.J., and Bugbee, B.B. 1998. Nitrogen balance for wheat canopies (*Triticum aestivum* cv. Veery 10) grown under elevated and ambient CO_2 concentrations. *Plant, Cell and Environ.* 21: 753-763.

Smith, D.M., Larson, B.C., Kelty, M.J., and Ashton, P.M.S. 1997. *The Practice of Silviculture* (9th eds), John Wiley & Sons, New York, 229p.

Smolander, H. and Lappi, J. 1985. Integration of a nonlinear function in a changing environment: estimating photosynthesis using mean and variance of radiation. *Agric. For. Meteorol.* 34: 83-91.

Song, Y.T., Zhou, D.W., and Zhang, H. 2013. Effects of vegetation height and density on soil temperature variations. *Chin. Sci. Bull.* 58: 907–912.

Sosebee, R.E. and Wiebe, H.H. 1971. Effect of water stress and clipping on photosynthate translocation in two grasses. *Agron. J.* 63: 14–17.

Souza, L. D., Souza, L., and Ledo, C. 2004. Water availability in citrus orchard, under pruning and subsoiling on Yellow Latosol of Coastal Table Land. *Revista Brasileira de Fruticultura*. 26: 69-73.

Stanciel, K., Mortley, D.G., Hileman, D.R., Loretan, P.A., Bonsi, C.K., and Hill, W.A. 2000. Growth, pod and seed yield, and gas exchange of hydroponically grown peanut in response to CO_2 enrichment. *Hort. Sci.* 35: 49-52.

Stape, J.L., Binkley, D., and Ryan, M.G. 2004. Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. *For. Ecol. Manag.* 193: 17–31.

Starostin, V.A. and Maslakov, E.L. 1989. The processes of crown formation and pruning in Scots pine. *For. Ecol. Manag.* 165:101-107.

Sternberg, P., Linder, S., Smolander, H., and Flower, J. 1994. Performances of LAI-2000 plant canopy analyser in estimating LAI of some scot pine stands. *Tree physiol.* 14: 981-995.

Stiptsov, V. and Botev, N. 1995. Phyto-productivity of plantation beech in relation to initial density and spacing. *Nauka Za Garata*. 32(3): 33-34.

Terjung, W.H. and Louie, S.S. 1972. Potential solar radiation on plant shapes. *Int. J. Biometeorol.* 16: 25-43.

Throssell, C.S., Carrow, R.N., and Milliken, G.A. 1987. Canopy temperature based irrigation scheduling indices for Kentucky bluegrass turf. *Crop Sci.* 27: 126–131.

Tjoelker, M.G., Oleksyn, J., and Reich, P.B. 1998. Seedlings of five boreal tree species differ in acclimation of net photosynthesis to elevated CO_2 and temperature. *Tree Physiol.* 18*:* 715-726.

Tognetti, R., Johnson, J.D., Michelozzi, M., and Raschi, A. 1998. Response of foliar metabolism in mature trees of *Quercus pubescens* and *Quercus ilex* to long-term elevated CO_2. *Environ. Exp. Bot.* 39: 233-245.

Tuomela, K., Otsamo, A., Kuusipalo, J., Vuokko, R., and Nikles, G. 1996. Effects of provenance variation and singling and pruning on early growth of Acacia mangium Willd. plantation on *Imperata cylindrica* (L.) dominated grassland. *For. Ecol. Manag.* 84: 241–249.

Valladares, 1999. Architecture, ecology and evolution of plant crowns. In: Pugnaire, V. (ed.), *Handbook of functional plant ecology*. Dekker, New York, pp. 21–194.

Vanden Beldt, R.J. and Williams, J.H. 1992. The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. *Agric. For. Meterol.* 60: 93–100.

Vandervelk, G. G. M. 1999. Effect of planting density on dry-matter production and evapotranspiration of tulips. *Acta Hortic.* 47: 31-38.

Vanwalleghem, T. and Meentemeyer, R.K. 2009. Predicting Forest Microclimate in Heterogeneous Landscapes. *Ecosyst.* 12: 1158–1172.

Vonarx, G., Dobbertin, M., and Rebetez, M. 2012. Spatio-temporal effects of forest canopy on understory microclimate in a long-term experiment in Switzerland. *Agric. For. Meteorol.* 116: 144–155.

Walcroft, A.S., Silvester, W.B., Grace, J.C., Carson, S.D., and Waring, R.H. 1996. Effects of branch length on carbon isotope discrimination in *Pinus radiata*. *Tree Physiol.* 16: 281–286.

Wallace, J. S. 1996. The water balance of mixed tree-crop systems. In: Ong C.K. and Huxley, P. (eds), *Tree-Crop Interactions: A Physiological Approach*. CAB International, Wallingford, United Kingdom, pp. 189–234.

Wang, K.Q., Wang B.T., Wang B.R., and Gao, H.P. 2002. Studies on the growth of forests with different density in the system of afforestation by water harvesting. *Scientia Silvae Sinicae.* 38(2): 54-60.

Waring, R.H. and Winner W.E. 1996. Constraints on terrestrial primary productivity in temperature forests along the Pacific Coast of North and South America. High-latitude rainforests and associated ecosystems of the West Coast of the Americas. *Nature.* 18: 89-102.

Warren, C., McGrath, J., and Adams, M. 2001. Water availability and carbon isotope discrimination in conifers. *Oecologia*. 127: 476–486.

Washusen, R., Waugh, G., Hudson, I., and Vinden, P., 2000. Appearance product potential of plantation hardwoods from medium rainfall areas of the southern Murray-Darling Basin. Green product recovery. *Aust. For.* 63: 66–71.

Wayne, P.M., Reekie, E.G., and Bazzaz, F.A. 1998. Elevated CO_2 ameliorates birch response to high temperature and frost stress: implications for modeling climate-induced geographic range shifts. *Oecologia*. 114: 335-342.

White, D.A., Crombie, D.S., Kinal, J., Battaglia, M., McGrath, J.F., Mendharn, D.S., and Walker, S.N. 2009. Managing productivity and drought risk in *Eucalyptus globulus* plantations in south-western Australia. *For. Ecol. Manag*. 259: 33–44.

Whitehead, D., Jarvis, P.G., and Waring, R.H. 1984. Stomatal conductance, transpiration, and resistance to water uptake in a *Pinus sylvestris* spacing experiment. *Can. J. For. Res.* 14: 692–700.

Whitehead, D., Livingston, N.J., Kelliher, F.M., Hogan, K.P., Pepin, S., McSeveny, T.M., and Byers, J.N. 1996. Response of transpiration and photosynthesis to a transient change in illuminated foliage area for a *Pinus radiata* D. Don tree. *Plant, Cell Environ.* 19: 949–957.

Wicklein, H.F., Christopher, D., Carter, M.E., and Smith, B.H. 2012. Edge effects on sapling characteristics and microclimate in a small temperate deciduous forest fragment. *Nat. Areas, J.* 32: 110–116.

Woodruff, D.R., Bond, B.J., Ritchie, G.A., and Scott, W. 2002. Effects of stand density on the growth of young Douglas-fir trees. *Can. J. For. Res.* 32: 420–427.

Wu, S.H., Jansson, P.E., and Kolari, P. 2012. The role of air and soil temperature in the seasonality of photosynthesis and transpiration in a boreal scot pine ecosystem. *Agric. For. Meteorol.* 156: 85–103.

Wullschleger, S.D., Meinzer, F.C., and Vertessy, R.A. 1998. A review of whole-plant water use studies in trees. *Tree Physiol.* 18: 499–512.

Yang, T.H., Short, R.D., and Fox, W.L.1990. Leaf temperature and stomatal resistance of a greenhouse cucumber crop. *Agric. For. Meteorol.* 51(4): 197–209.

Zeppel, M.J.B., Murray, B.R., Barton, C., and Eamus, D. 2004. Seasonal responses of xylem sap velocity to vapour pressure deficit and solar radiation during drought in a stand of native trees in temperate Australia. *Funct. Plant Biol.* 31: 461–470.

Zhang, J., Guo, B., Jiang, Q., Ru, H., and Wang, Z. 2013. Study on microclimate characteristics and vertical variation of potential evapotranspiration of *Robinia pseudoacacia* forest in loess plateau of china. *Adv. meteorol.* 3: 11-24.

Zhang, Y.B., Duan, B.L., Qiao, Y.Z., Wang, K.Y., Korpelainen, H., and Li, C.Y. 2008. Leaf photosynthesis of *Betula albosinensis* seedlings as affected by elevated CO_2 and planting density. *For. Ecol. Manag.* 255: 1937–1944.

Zhang, Z.K., Liu, S.Q., Liu, S.H., and Huang, Z.J. 2010. Estimation of cucumber evapotranspiration in solar greenhouse in northeast China. *Agric. Sci. China* 9(4): 512–518.

Zhao, H., Yi, X., Zhou, R., Zhao, X., Zhang, T., and Drake, S. 2006. Wind erosion and sand accumulation effects on soil properties in Horqin Sandy Farmland, Inner Mongolia, Catena. *For. Sci.* 65: 571–579.

Zheng, W. 2011. The study on plant seedling growth strategy. Ph.D. thesis, Northeast Normal University, Changchun.

Zhu, F.R., Hu, H.B., and Yang, W.R. 2013. Soil temperature and moisture content characteristics of oak forests in hilly region in Jiangsu. *Hubei Agric. Sci.* 1: 39–42.

Zoungrana, I., Yélémou, B. and Hien, F. 1993. Etude des relations neem-sol-sorgho dans les systèmes agroforestiers du Bulkiemdé (Burkina Faso). In: *International symposium on agroforestry parklands in the semi-arid lands of West Africa*, 25–27 October, 1993. ICRAF/IRBET/CILSS/LTC, Ouagadougou, Burkina Faso.

Zweifel, R., Bohm, J.P., and Hasler, R. 2002. Midday stomatal closure in Norway spruce-reactions in the upper and lower crown. *Tree Physiol.* 22: 1125–1136.

Appendices

APPENDIX I

Results of univariate analysis for microclimate variables during summer season

I. Results of univariate analysis for air temperature at the height of 5 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	124514.397[a]	9	13834.933	2881.132	.000
spacing	133.788	3	44.596	9.287	.000
pruning	18.955	1	18.955	3.947	.049
spacing * pruning	34.916	3	11.639	2.424	.070
Error	518.606	108	4.802		
Total	125033.003	117			

a. R Squared = .996 (Adjusted R Squared = .996)

II. Results of univariate analysis for air temperature at the height of 10 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	124684.654[a]	9	13853.850	3487.833	.000
spacing	99.190	3	33.063	8.324	.000
pruning	15.694	1	15.694	3.951	.049
spacing * pruning	47.320	3	15.773	3.971	.010
Error	428.982	108	3.972		
Total	125113.636	117			

a. R Squared = .997 (Adjusted R Squared = .996)

III. Results of univariate analysis for relative humidity at the height of 5 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	385698.231[a]	9	42855.359	1046.016	.000
spacing	454.952	3	151.651	3.701	.014
pruning	127.163	1	127.163	3.104	.081
spacing * pruning	707.644	3	235.881	5.757	.001
Error	4424.769	108	40.970		
Total	390123.000	117			

a. R Squared = .989 (Adjusted R Squared = .988)

IV. Results of univariate analysis for relative humidity at the height of 10 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	396947.769[a]	9	44105.308	1115.745	.000
spacing	454.490	3	151.497	3.832	.012
pruning	160.010	1	160.010	4.048	.047
spacing * pruning	447.490	3	149.163	3.773	.013
Error	4269.231	108	39.530		
Total	401217.000	117			

a. R Squared = .989 (Adjusted R Squared = .988)

V. Results of univariate analysis for PAR at the height of 5 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	13101088.231[a]	9	1455676.470	72.314	.000
spacing	183136.337	3	61045.446	3.033	.032
pruning	26209.625	1	26209.625	1.302	.256
spacing * pruning	20411.260	3	6803.753	.338	.798
Error	2174032.769	108	20129.933		
Total	15275121.000	117			

a. R Squared = .858 (Adjusted R Squared = .846)

VI. Results of univariate analysis for PAR at the height of 10 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	13888120.077[a]	9	1543124.453	72.523	.000
spacing	155745.106	3	51915.035	2.440	.068
pruning	20244.240	1	20244.240	.951	.332
spacing * pruning	28603.567	3	9534.522	.448	.719
Error	2298000.923	108	21277.786		
Total	16186121.000	117			

a. R Squared = .858 (Adjusted R Squared = .846)

VII. Results of univariate analysis for soil temperature at 5 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	111178.039[a]	9	12353.115	6229.893	.000
spacing	212.636	3	70.879	35.745	.000
pruning	.002	1	.002	.001	.978
spacing * pruning	.385	3	.128	.065	.978
Error	214.151	108	1.983		
Total	111392.190	117			

a. R Squared = .998 (Adjusted R Squared = .998)

VIII. Results of univariate analysis for soil temperature at 10 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	105230.121[a]	9	11692.236	6452.892	.000
spacing	180.545	3	60.182	33.214	.000
pruning	.075	1	.075	.042	.839
spacing * pruning	1.037	3	.346	.191	.902
Error	195.689	108	1.812		
Total	105425.810	117			

a. R Squared = .998 (Adjusted R Squared = .998)

IX. Results of univariate analysis for soil temperature at 20 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	104061.981[a]	9	11562.442	7015.839	.000
spacing	263.070	3	87.690	53.208	.000
pruning	9.615E-005	1	9.615E-005	.000	.994
spacing * pruning	.091	3	.030	.018	.997
Error	177.989	108	1.648		
Total	104239.970	117			

a. R Squared = .998 (Adjusted R Squared = .998)

X. Results of univariate analysis for soil moisture content at 5 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	17455.619[a]	9	1939.513	382.182	.000
spacing	187.586	3	62.529	12.321	.000
pruning	12.289	1	12.289	2.422	.123
spacing * pruning	32.460	3	10.820	2.132	.100
Error	548.083	108	5.075		
Total	18003.702	117			

a. R Squared = .970 (Adjusted R Squared = .967)

XI. Results of univariate analysis for soil moisture content at 10 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	21239.913[a]	9	2359.990	400.025	.000
spacing	55.245	3	18.415	3.121	.029
pruning	2.334	1	2.334	.396	.531
spacing * pruning	28.008	3	9.336	1.582	.198
Error	637.158	108	5.900		
Total	21877.071	117			

a. R Squared = .971 (Adjusted R Squared = .968)

XII. Results of univariate analysis for soil moisture content at 20 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	24166.590[a]	9	2685.177	444.484	.000
spacing	135.674	3	45.225	7.486	.000
pruning	18.913	1	18.913	3.131	.080
spacing * pruning	3.999	3	1.333	.221	.882
Error	652.440	108	6.041		
Total	24819.030	117			

a. R Squared = .974 (Adjusted R Squared = .972)

XIII. Results of univariate analysis for soil moisture content at 30 cm depth during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	27250.357[a]	9	3027.817	435.918	.000
spacing	278.713	3	92.904	13.376	.000
pruning	6.135	1	6.135	.883	.349
spacing * pruning	12.573	3	4.191	.603	.614
Error	750.151	108	6.946		
Total	28000.509	117			

a. R Squared = .973 (Adjusted R Squared = .971)

XIV. Results of univariate analysis for relative water content (RWC) during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	491876.033[a]	8	61484.504	1365.262	.000
spacing	707.311	3	235.770	5.235	.002
pruning	2.802	1	2.802	.062	.804
spacing * pruning	173.880	3	57.960	1.287	.283
Error	4323.355	96	45.035		
Total	496199.388	104			

a. R Squared = .991 (Adjusted R Squared = .991)

XV. Results of univariate analysis for canopy-air temperature difference (CATD) during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	420.490[a]	8	52.561	35.255	.000
spacing	14.335	3	4.778	3.205	.027
pruning	.578	1	.578	.387	.535
spacing * pruning	.189	3	.063	.042	.988
Error	143.125	96	1.491		
Total	563.615	104			

a. R Squared = .746 (Adjusted R Squared = .725)

XVI. Results of univariate analysis for evapotranspiration (ET)) during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	4085.617[a]	8	510.702	278.390	.000
spacing	28.695	3	9.565	5.214	.002
pruning	.154	1	.154	.084	.773
spacing * pruning	7.258	3	2.419	1.319	.273
Error	176.111	96	1.834		
Total	4261.728	104			

a. R Squared = .959 (Adjusted R Squared = .955)

APPENDIX II

Results of univariate analysis for microclimate variables during pre-monsoon season

I. Results of univariate analysis for air temperature at the height of 5 m above the ground level during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	82843.239[a]	9	9204.804	2988.723	.000
spacing	90.733	3	30.244	9.820	.000
pruning	4.061	1	4.061	1.319	.255
spacing * pruning	5.368	3	1.789	.581	.629
Error	221.749	72	3.080		
Total	83064.987	81			

a. R Squared = .997 (Adjusted R Squared = .997)

II. Results of univariate analysis for air temperature at the height of 10 m above the ground level during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	85559.660[a]	9	9506.629	3323.135	.000
spacing	76.429	3	25.476	8.906	.000
pruning	2.347	1	2.347	.820	.368
spacing * pruning	8.846	3	2.949	1.031	.384
Error	205.973	72	2.861		
Total	85765.633	81			

a. R Squared = .998 (Adjusted R Squared = .997)

III. Results of univariate analysis for relative humidity at the height of 5 m above the ground level during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	302117.000[a]	9	33568.556	320.719	.000
spacing	91.264	3	30.421	.291	.832
pruning	115.014	1	115.014	1.099	.298
spacing * pruning	196.264	3	65.421	.625	.601
Error	7536.000	72	104.667		
Total	309653.000	81			

a. R Squared = .976 (Adjusted R Squared = .973)

IV. Results of univariate analysis for relative humidity at the height of 10 m above the ground level during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	320233.000[a]	9	35581.444	339.950	.000
spacing	91.264	3	30.421	.291	.832
pruning	115.014	1	115.014	1.099	.298
spacing * pruning	196.264	3	65.421	.625	.601
Error	7536.000	72	104.667		
Total	327769.000	81			

a. R Squared = .977 (Adjusted R Squared = .974)

V. Results of univariate analysis for PAR at the height of 5 m above the ground level during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	6941887.111[a]	9	771320.790	91.976	.000
spacing	121279.611	3	40426.537	4.821	.004
pruning	696.889	1	696.889	.083	.774
spacing * pruning	83622.111	3	27874.037	3.324	.024
Error	603796.889	72	8386.068		
Total	7545684.000	81			

a. R Squared = .920 (Adjusted R Squared = .910)

VI. Results of univariate analysis for PAR at the height of 10 m above the ground level during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	7358073.111[a]	9	817563.679	97.491	.000
spacing	127478.111	3	42492.704	5.067	.003
pruning	696.889	1	696.889	.083	.774
spacing * pruning	83622.111	3	27874.037	3.324	.024
Error	603796.889	72	8386.068		
Total	7961870.000	81			

a. R Squared = .924 (Adjusted R Squared = .915)

VII. Results of univariate analysis for soil temperature at 5 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	74072.464[a]	9	8230.274	9778.773	.000
spacing	96.130	3	32.043	38.072	.000
pruning	.065	1	.065	.078	.781
spacing * pruning	4.579	3	1.526	1.813	.152
Error	60.599	72	.842		
Total	74133.063	81			

a. R Squared = .999 (Adjusted R Squared = .999)

VIII. Results of univariate analysis for soil temperature at 10 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	70151.822[a]	9	7794.647	6959.698	.000
spacing	156.868	3	52.289	46.688	.000
pruning	.040	1	.040	.036	.850
spacing * pruning	1.093	3	.364	.325	.807
Error	80.638	72	1.120		
Total	70232.460	81			

a. R Squared = .999 (Adjusted R Squared = .999)

IX. Results of univariate analysis for soil temperature at 20 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	68164.766[a]	9	7573.863	10583.678	.000
spacing	137.655	3	45.885	64.119	.000
pruning	.201	1	.201	.280	.598
spacing * pruning	2.099	3	.700	.978	.408
Error	51.524	72	.716		
Total	68216.290	81			

a. R Squared = .999 (Adjusted R Squared = .999)

X. Results of univariate analysis for soil moisture content at 5 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	15148.479[a]	9	1683.164	648.924	.000
spacing	175.379	3	58.460	22.538	.000
pruning	17.366	1	17.366	6.695	.012
spacing * pruning	9.243	3	3.081	1.188	.320
Error	186.752	72	2.594		
Total	15335.231	81			

a. R Squared = .988 (Adjusted R Squared = .986)

XI. Results of univariate analysis for soil moisture content at 10 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	17087.349[a]	9	1898.594	831.325	.000
spacing	111.730	3	37.243	16.308	.000
pruning	18.140	1	18.140	7.943	.006
spacing * pruning	18.866	3	6.289	2.754	.049
Error	164.435	72	2.284		
Total	17251.784	81			

a. R Squared = .990 (Adjusted R Squared = .989)

XII. Results of univariate analysis for soil moisture content at 20 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	21202.665[a]	9	2355.852	959.224	.000
spacing	194.565	3	64.855	26.407	.000
pruning	7.113	1	7.113	2.896	.093
spacing * pruning	12.920	3	4.307	1.754	.164
Error	176.832	72	2.456		
Total	21379.497	81			

a. R Squared = .992 (Adjusted R Squared = .991)

XIII. Results of univariate analysis for soil moisture content at 30 cm depth during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	25671.431[a]	9	2852.381	1202.262	.000
spacing	131.442	3	43.814	18.467	.000
pruning	2.153	1	2.153	.907	.344
spacing * pruning	22.516	3	7.505	3.163	.030
Error	170.821	72	2.373		
Total	25842.252	81			

a. R Squared = .993 (Adjusted R Squared = .993)

XIV. Results of univariate analysis for relative water content (RWC) during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	364036.873[a]	8	45504.609	7203.575	.000
spacing	236.443	3	78.814	12.477	.000
pruning	199.101	1	199.101	31.519	.000
spacing * pruning	167.789	3	55.930	8.854	.000
Error	404.285	64	6.317		
Total	364441.158	72			

a. R Squared = .999 (Adjusted R Squared = .999)

XV. Results of univariate analysis for canopy-air temperature difference (CATD) during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	25.180[a]	8	3.147	3.893	.001
spacing	6.076	3	2.025	2.505	.067
pruning	.096	1	.096	.119	.731
spacing * pruning	3.579	3	1.193	1.475	.230
Error	51.740	64	.808		
Total	76.920	72			

a. R Squared = .327 (Adjusted R Squared = .243)

XVI. Results of univariate analysis for evapotranspiration (ET) during pre-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	2236.171[a]	8	279.521	231.581	.000
spacing	16.122	3	5.374	4.452	.007
pruning	.889	1	.889	.736	.394
spacing * pruning	34.556	3	11.519	9.543	.000
Error	77.249	64	1.207		
Total	2313.420	72			

a. R Squared = .967 (Adjusted R Squared = .962)

APPENDIX III

Results of univariate analysis for microclimate variables during monsoon season

I. Results of univariate analysis for air temperature at the height of 5 m above the ground level during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	91406.162[a]	9	10156.240	6300.779	.000
spacing	1.947	3	.649	.403	.751
pruning	.000	1	.000	.000	.987
spacing * pruning	11.530	3	3.843	2.384	.074
Error	159.578	99	1.612		
Total	91565.740	108			

a. R Squared = .998 (Adjusted R Squared = .998)

II. Results of univariate analysis for air temperature at the height of 10 m above the ground level during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	89171.748[a]	9	9907.972	11188.212	.000
spacing	.835	3	.278	.314	.815
pruning	.094	1	.094	.106	.746
spacing * pruning	4.932	3	1.644	1.856	.142
Error	87.672	99	.886		
Total	89259.420	108			

a. R Squared = .999 (Adjusted R Squared = .999)

III. Results of univariate analysis for relative humidity at the height of 5 m above the ground level during summer season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	571616.333[a]	9	63512.926	1599.266	.000
spacing	61.917	3	20.639	.520	.670
pruning	.167	1	.167	.004	.948
spacing * pruning	1.583	3	.528	.013	.998
Error	3931.667	99	39.714		
Total	575548.000	108			

a. R Squared = .993 (Adjusted R Squared = .993)

IV. Results of univariate analysis for relative humidity at the height of 10 m above the ground level during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	600982.667[a]	9	66775.852	1426.178	.000
spacing	59.542	3	19.847	.424	.736
pruning	.667	1	.667	.014	.905
spacing * pruning	20.417	3	6.806	.145	.932
Error	4635.333	99	46.822		
Total	605618.000	108			

a. R Squared = .992 (Adjusted R Squared = .992)

V. Results of univariate analysis for PAR at the height of 5 m above the ground level during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	3617412.917[a]	9	401934.769	44.589	.000
spacing	70532.750	3	23510.917	2.608	.056
pruning	12880.667	1	12880.667	1.429	.235
spacing * pruning	25550.583	3	8516.861	.945	.422
Error	892402.083	99	9014.162		
Total	4509815.000	108			

a. R Squared = .802 (Adjusted R Squared = .784)

VI. Results of univariate analysis for PAR at the height of 10 m above the ground level during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	4007622.917[a]	9	445291.435	49.399	.000
spacing	73166.750	3	24388.917	2.706	.049
pruning	12880.667	1	12880.667	1.429	.235
spacing * pruning	25550.583	3	8516.861	.945	.422
Error	892402.083	99	9014.162		
Total	4900025.000	108			

a. R Squared = .818 (Adjusted R Squared = .801)

VII. Results of univariate analysis for soil temperature at 5 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	71461.696[a]	9	7940.188	3475.238	.000
spacing	.271	3	.090	.040	.989
pruning	2.130	1	2.130	.932	.337
spacing * pruning	6.199	3	2.066	.904	.442
Error	226.194	99	2.285		
Total	71687.890	108			

a. R Squared = .997 (Adjusted R Squared = .997)

VIII. Results of univariate analysis for soil temperature at 10 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	67901.517[a]	9	7544.613	4089.035	.000
spacing	1.239	3	.413	.224	.880
pruning	.920	1	.920	.499	.482
spacing * pruning	4.872	3	1.624	.880	.454
Error	182.663	99	1.845		
Total	68084.180	108			

a. R Squared = .997 (Adjusted R Squared = .997)

IX. Results of univariate analysis for soil temperature at 20 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	65193.907[a]	9	7243.767	4579.320	.000
spacing	.686	3	.229	.145	.933
pruning	.683	1	.683	.432	.513
spacing * pruning	.724	3	.241	.153	.928
Error	156.603	99	1.582		
Total	65350.510	108			

a. R Squared = .998 (Adjusted R Squared = .997)

X. Results of univariate analysis for soil moisture content at 5 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	53009.494[a]	9	5889.944	215.443	.000
spacing	148.381	3	49.460	1.809	.150
pruning	58.750	1	58.750	2.149	.146
spacing * pruning	19.955	3	6.652	.243	.866
Error	2706.535	99	27.339		
Total	55716.029	108			

a. R Squared = .951 (Adjusted R Squared = .947)

XI. Results of univariate analysis for soil moisture content at 10 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	52725.889[a]	9	5858.432	187.386	.000
spacing	18.252	3	6.084	.195	.900
pruning	16.099	1	16.099	.515	.475
spacing * pruning	17.985	3	5.995	.192	.902
Error	3063.864	98	31.264		
Total	55789.753	107			

a. R Squared = .945 (Adjusted R Squared = .940)

XII. Results of univariate analysis for soil moisture content at 20 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	65413.392[a]	9	7268.155	247.613	.000
spacing	13.488	3	4.496	.153	.927
pruning	52.392	1	52.392	1.785	.185
spacing * pruning	6.837	3	2.279	.078	.972
Error	2905.940	99	29.353		
Total	68319.332	108			

a. R Squared = .957 (Adjusted R Squared = .954)

XIII. Results of univariate analysis for soil moisture content at 30 cm depth during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	76715.925[a]	9	8523.992	216.721	.000
spacing	9.959	3	3.320	.084	.968
pruning	5.900	1	5.900	.150	.699
spacing * pruning	89.704	3	29.901	.760	.519
Error	3893.829	99	39.332		
Total	80609.754	108			

a. R Squared = .952 (Adjusted R Squared = .947)

XIV. Results of univariate analysis for relative water content (RWC) during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	661363.713[a]	8	82670.464	2912.739	.000
spacing	123.273	3	41.091	1.448	.234
pruning	46.245	1	46.245	1.629	.205
spacing * pruning	100.830	3	33.610	1.184	.320
Error	2497.650	88	28.382		
Total	663861.362	96			

a. R Squared = .996 (Adjusted R Squared = .996)

XV. Results of univariate analysis for canopy-air temperature difference (CATD) during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	702.700[a]	8	87.838	112.545	.000
spacing	.504	3	.168	.215	.885
pruning	1.148	1	1.148	1.471	.228
spacing * pruning	1.531	3	.510	.654	.583
Error	68.681	88	.780		
Total	771.381	96			

a. R Squared = .911 (Adjusted R Squared = .903)

XVI. Results of univariate analysis for evapotranspiration (ET) during monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	941.777[a]	8	117.722	93.766	.000
spacing	4.959	3	1.653	1.317	.274
pruning	2.282	1	2.282	1.817	.181
spacing * pruning	4.521	3	1.507	1.200	.314
Error	110.483	88	1.255		
Total	1052.260	96			

a. R Squared = .895 (Adjusted R Squared = .885)

APPENDIX IV

Results of univariate analysis for microclimate variables during post-monsoon season

I. Results of univariate analysis for air temperature at the height of 5 m above the ground level during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	109308.030[a]	9	12145.337	8401.847	.000
spacing	16.655	3	5.552	3.840	.012
pruning	1.831	1	1.831	1.267	.263
spacing * pruning	4.416	3	1.472	1.018	.388
Error	156.120	108	1.446		
Total	109464.150	117			

a. R Squared = .999 (Adjusted R Squared = .998)

II. Results of univariate analysis for air temperature at the height of 10 m above the ground level during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	105940.085[a]	9	11771.121	8306.604	.000
spacing	8.965	3	2.988	2.109	.103
pruning	.779	1	.779	.550	.460
spacing * pruning	1.476	3	.492	.347	.791
Error	153.045	108	1.417		
Total	106093.130	117			

a. R Squared = .999 (Adjusted R Squared = .998)

III. Results of univariate analysis for relative humidity at the height of 5 m above the ground level during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	544910.615[a]	9	60545.624	1048.681	.000
spacing	18.567	3	6.189	.107	.956
pruning	40.625	1	40.625	.704	.403
spacing * pruning	86.260	3	28.753	.498	.684
Error	6235.385	108	57.735		
Total	551146.000	117			

a. R Squared = .989 (Adjusted R Squared = .988)

IV. Results of univariate analysis for relative humidity at the height of 10 m above the ground level during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	573906.615[a]	9	63767.402	1104.483	.000
spacing	18.567	3	6.189	.107	.956
pruning	40.625	1	40.625	.704	.403
spacing * pruning	86.260	3	28.753	.498	.684
Error	6235.385	108	57.735		
Total	580142.000	117			

a. R Squared = .989 (Adjusted R Squared = .988)

V. Results of univariate analysis for PAR at the height of 5 m above the ground level during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	6305957.923[a]	9	700661.991	202.549	.000
spacing	80405.183	3	26801.728	7.748	.000
pruning	625.240	1	625.240	.181	.672
spacing * pruning	13563.567	3	4521.189	1.307	.276
Error	373595.077	108	3459.214		
Total	6679553.000	117			

a. R Squared = .944 (Adjusted R Squared = .939)

VI. Results of univariate analysis for PAR at the height of 10 m above the ground level during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	6796773.923[a]	9	755197.103	218.315	.000
spacing	78183.183	3	26061.061	7.534	.000
pruning	504.240	1	504.240	.146	.703
spacing * pruning	13853.567	3	4617.856	1.335	.267
Error	373595.077	108	3459.214		
Total	7170369.000	117			

a. R Squared = .948 (Adjusted R Squared = .944)

VII. Results of univariate analysis for soil temperature at 5 cm depth post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	91632.958[a]	9	10181.440	26323.551	.000
spacing	78.846	3	26.282	67.950	.000
pruning	8.482	1	8.482	21.929	.000
spacing * pruning	1.126	3	.375	.970	.410
Error	41.772	108	.387		
Total	91674.730	117			

a. R Squared = 1.000 (Adjusted R Squared = 1.000)

VIII. Results of univariate analysis for soil temperature at 10 cm depth during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	85980.076[a]	9	9553.342	33658.449	.000
spacing	68.867	3	22.956	80.878	.000
pruning	.832	1	.832	2.930	.090
spacing * pruning	28.172	3	9.391	33.085	.000
Error	30.654	108	.284		
Total	86010.730	117			

a. R Squared = 1.000 (Adjusted R Squared = 1.000)

IX. Results of univariate analysis for soil temperature at 20 cm depth during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	80965.122[a]	9	8996.125	27072.832	.000
spacing	30.213	3	10.071	30.308	.000
pruning	4.612	1	4.612	13.878	.000
spacing * pruning	.547	3	.182	.549	.650
Error	35.888	108	.332		
Total	81001.010	117			

a. R Squared = 1.000 (Adjusted R Squared = 1.000)

X. Results of univariate analysis for soil moisture content at 5 cm depth during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	38914.426[a]	9	4323.825	1116.996	.000
spacing	53.796	3	17.932	4.632	.004
pruning	84.456	1	84.456	21.818	.000
spacing * pruning	16.120	3	5.373	1.388	.250
Error	418.062	108	3.871		
Total	39332.488	117			

a. R Squared = .989 (Adjusted R Squared = .988)

XI. Results of univariate analysis for soil moisture content at 10 cm depth during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	38744.195[a]	9	4304.911	1530.770	.000
spacing	55.123	3	18.374	6.534	.000
pruning	36.285	1	36.285	12.902	.000
spacing * pruning	33.708	3	11.236	3.995	.010
Error	303.723	108	2.812		
Total	39047.919	117			

a. R Squared = .992 (Adjusted R Squared = .992)

XII. Results of univariate analysis for soil moisture content at 20 cm depth during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	48774.771[a]	9	5419.419	2439.090	.000
spacing	94.052	3	31.351	14.110	.000
pruning	28.781	1	28.781	12.953	.000
spacing * pruning	6.588	3	2.196	.988	.401
Error	239.965	108	2.222		
Total	49014.737	117			

a. R Squared = .995 (Adjusted R Squared = .995)

XIII. Results of univariate analysis for soil moisture content at 30 cm depth during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	60685.329[a]	9	6742.814	1924.082	.000
spacing	104.916	3	34.972	9.979	.000
pruning	23.894	1	23.894	6.818	.010
spacing * pruning	5.246	3	1.749	.499	.684
Error	378.479	108	3.504		
Total	61063.808	117			

a. R Squared = .994 (Adjusted R Squared = .993)

XIV. Results of univariate analysis for relative water content (RWC) during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	620324.110[a]	8	77540.514	3624.316	.000
spacing	137.836	3	45.945	2.148	.099
pruning	216.375	1	216.375	10.114	.002
spacing * pruning	212.929	3	70.976	3.318	.023
Error	2053.874	96	21.395		
Total	622377.984	104			

a. R Squared = .997 (Adjusted R Squared = .996)

XV. Results of univariate analysis for canopy-air temperature difference (CATD) during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	73.662[a]	8	9.208	9.895	.000
spacing	2.585	3	.862	.926	.431
pruning	2.714	1	2.714	2.916	.091
spacing * pruning	11.027	3	3.676	3.950	.011
Error	89.335	96	.931		
Total	162.997	104			

a. R Squared = .452 (Adjusted R Squared = .406)

XVI. Results of univariate analysis for evapotranspiration (ET) during post-monsoon season

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	1424.192[a]	8	178.024	530.958	.000
spacing	10.540	3	3.513	10.479	.000
pruning	1.831	1	1.831	5.461	.022
spacing * pruning	4.294	3	1.431	4.269	.007
Error	32.188	96	.335		
Total	1456.380	104			

a. R Squared = .978 (Adjusted R Squared = .976)

APPENDIX V

Results of univariate analysis for growth parameters and WUE of *Acacia mangium*

I. Results of univariate analysis for diameter of *Acacia mangium*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	9.201[a]	9	1.022	843.612	.000
spacing	.140	3	.047	38.587	.000
pruning	.012	1	.012	10.288	.001
spacing * pruning	.002	3	.001	.596	.618
Error	.460	380	.001		
Total	9.661	389			

a. R Squared = .952 (Adjusted R Squared = .951)

II. Results of univariate analysis for height of *Acacia mangium*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	92050.738[a]	9	10227.860	844.495	.000
spacing	1413.068	3	471.023	38.891	.000
pruning	128.467	1	128.467	10.607	.001
spacing * pruning	22.816	3	7.605	.628	.597
Error	4602.262	380	12.111		
Total	96653.000	389			

a. R Squared = .952 (Adjusted R Squared = .951)

III. Results of univariate analysis for aboveground standing biomass (Kg tree^{-1}) of *Acacia mangium*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	4789407.854[a]	9	532156.428	129.943	.000
spacing	497947.265	3	165982.422	40.530	.000
pruning	49527.016	1	49527.016	12.094	.001
spacing * pruning	12150.945	3	4050.315	.989	.398
Error	1556217.524	380	4095.309		
Total	6345625.377	389			

a. R Squared = .755 (Adjusted R Squared = .749)

IV. Results of univariate analysis for aboveground standing biomass (Mg ha^{-1}) of *Acacia mangium* stand

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	32273646.590[a]	8	4034205.824	89.105	.000
spacing	2719440.060	3	906480.020	20.022	.000
pruning	215818.218	1	215818.218	4.767	.030
spacing * pruning	335936.515	3	111978.838	2.473	.061
Error	17204360.579	380	45274.633		
Total	49478007.170	388			

a. R Squared = .652 (Adjusted R Squared = .645)

V. Results of univariate analysis for WUE of *Acacia mangium*

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	212901.049[a]	8	26612.631	20999.087	.000
spacing	40.696	3	13.565	10.704	.000
pruning	1.933	1	1.933	1.525	.218
spacing * pruning	16.348	3	5.449	4.300	.005
Error	481.583	380	1.267		
Total	213382.632	388			

a. R Squared = .998 (Adjusted R Squared = .998)

INFLUENCE OF PLANTING DENSITY AND PRUNING ON THERMAL, RADIATIVE AND MOISTURE REGIMES IN *Acacia mangium* Willd. STAND

By

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ABSTRACT

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COLLEGE OF FORESTRY

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ABSTRACT

A study on influence of planting density and pruning on thermal, radiative and moisture regimes and water use efficiency of *Acacia mangium* was conducted at Livestock Research Station, Thiruvizhamkunnu (11^{0} 12′ N, 76^{0} 21′ E) during the period 2014-15. The experiment was laid out in a factorial RBD with two factors (density and pruning) replicated thrice. Density treatments include 625, 1250 , 2500 and 5000 trees/ha, while pruning treatments included pruning up to 50 % height of trees and no pruning. Measurements on air temperature (AT), relative humidity (RH), photosynthetically active radiation (PAR) at 5 and 10 m above ground; soil moisture content (SMC) at 5, 10, 20 and 30 cm depth, soil temperature (ST) at 5, 10 and 20 cm depths, relative water content (RWC) and canopy air temperature difference (CATD) were taken on a weekly interval for one year. The weekly observations were then grouped into summer, pre-monsoon, monsoon and post monsoon season for analysis. Observations on DBH, tree height, LAI and PAR were taken once during the study period. Evapotranspiration, biomass and WUE were estimated using appropriate methodologies.

Diameter at breast height, tree height and individual tree biomass increased with decreasing density, while aboveground standing biomass on stand level and LAI followed a reverse trend. The unpruned stand had significantly higher DBH and biomass as compared to that of the pruned stand. Biometric characters had positive correlations with the AT, PAR at 5 and 10 m above the ground level, RWC, ST (5 , 10 and 20 cm) and SMC (20 and 30 cm depth), while it was negatively correlated with the evapotranspiration and SMC (5 and 10 cm depth). No significant correlation was found between CATD and RH (5 and 10 m above ground).

Air temperature (5 and 10 m above ground) and ST (at depths of 5, 10 and 20 cm) were negatively correlated to planting density and LAI. It was found that the largest differences with open area for these parameters were recorded at a density of 5000 trees/ha, throughout all seasons. It was found that there is an average difference of 2.62° C and 2.52° C between AT in the *Acacia mangium* stand compared to the open area at 5 m and 10 m above the ground level respectively. Soil temperature (5, 10 and 20 cm depth) was negatively correlated with the SMC (5, 10, 20 and 30 cm depth). An average ST difference of 2.6° C, 2.6° C and 2.5 ° C was found between the *Acacia mangium* stand and open area at depth of 5, 10, 20 and 30 cm depth respectively. Pruning did not affect both the AT and ST except, ST at 5 cm depth during the post-monsoon season.

CATD was positive and higher in high density treatments during the summer and pre-monsoon, while it remained negative and unaffected by density during the other seasons. CATD was negatively correlated to evapotranspiration, RWC, and SMC at various depths.

Influence of planting density on RH was evident only during the summer season. . It was found that there is an average difference of 7.51 % and 5.76 % in RH between the *Acacia mangium* stand and open area at 5 m and 10 m above the ground level respectively. The RWC, evapotranspiration and SMC (20 and 30 cm depth) were significantly higher in the low planting density, while reverse trend was noticed for SMC (5 cm and 10 cm depth). An average SMC difference of 4.50 %, 3.70 %, 3.32 % and 3.11 % was found between the *Acacia mangium* stand and open area at depth of 5, 10, 20 and 30 cm depth respectively. The RWC was significantly higher in the pruned stands during the pre-monsoon and post-monsoon season, while no differences were observed during the summer and monsoon season. Water use efficiency (WUE) of *Acacia mangium* stand was not significantly affected by the planting density and pruning treatments.

Radiation below the canopy was found negatively correlated to planting density and LAI, while it was not influenced by pruning. It was found that there is an average difference of 450 W/m^2 and 466 W/m^2 between the *Acacia mangium* stand and open area at 5 m and 10 m above the ground level respectively The average mid-day PAR transmittance from the unpruned stand (5000 trees/ha) to the pruned stand (625 trees/ha) ranged from 24.27 % to 54.72 % of incident PAR above the canopy. There was strong relationship between the PAR and LAI. The light extinction coefficient (K) for *Acacia mangium* stand was estimated to be 0.328.