

LYSIMETRIC STUDIES ON SOME TREE SPECIES TO EVALUATE THEIR BIODRAINAGE POTENTIAL

BY

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CERTIFICATE – I

This is to certify that this dissertation entitled, “**Lysimetric studies on some tree species to evaluate their biodrainage potential**” submitted for the degree of **Doctor of Philosophy** in the subject of **Plant Physiology** to the Chaudhary Charan Singh Haryana Agricultural University, Hisar is a bonafide research work carried out by **Sukham Madaan (Admn. No. 2006BS30D)** under my supervision and that no part of this dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE – II

This is to certify that this dissertation entitled, “**Lysimetric studies on some tree species to evaluate their biodrainage potential**”, submitted by **Sukham Madaan** to the Chaudhary Charan Singh Haryana Agricultural University, Hisar in partial fulfillment of the requirements for the degree of **Doctor of Philosophy**, in the subject of **Plant Physiology** has been approved by the Student’s Advisory Committee after an oral examination on the same in collaboration with an External Examiner.

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ABBREVIATIONS

Avp	:	Actual vapor pressure
DBH	:	Diameter at breast height
DPX	:	Di-n-butylphthalate xylene
E	:	Transpiration
Ep	:	Potential evaporation
FAA	:	Formalin-acetic-acid-alcohol
GBH	:	Girth at breast height
g_s	:	Stomatal conductance
HNO_3	:	Nitric acid
KH_2PO_4	:	Potassium dihydrogen phosphate
LA	:	Leaf area
Rad	:	Radiation
RH	:	Relative humidity
SH	:	Sunshine hours
T	:	Temperature
VPD	:	Vapor pressure deficit
Wb	:	Water biodrained
WS	:	Wind speed

“The fact that trees are large and not easy to handle...increases the difficulties (of measuring the water requirement of trees), but they should not be insurmountable; for not really satisfactory results can be expected until more data are obtained on forest trees and stands under natural conditions, supplemented by laboratory work on a scale comparable with the size of the problem involved.”

Raber, 1937

Recognizing irrigation as a cardinal input for increasing and stabilizing yields has prompted economies throughout the world to expand their canal irrigation potential manifold during the past 60 years or so. Where ever such import and liberal use of water involved in arid regions, the problem of water logging and salinity surfaced. Presently, about one-third of the world's irrigated area faces the threat of water logging; about 60 million ha is already waterlogged and 20 million ha is salt affected (Heuperman *et al.*, 2002). The state of Haryana (north west India) itself typifies this scenario. In south west Haryana about 200 km long axis of arable land comprising the districts of Jhajjr-Rohtak-Hisar-Fatehabad-Sirsa forms an inland basin with no natural drainage. This region is mostly underlain by saline ground water. Till early 1950s rainfed agriculture was practiced here and the saline water table remained deep in equilibrium as the water requirement was met primarily with rainfall, though only partially. With the intra-basin transfer of Sutlej River (Indus basin) waters to the area, an era of liberal use of irrigation water and high productivity prevailed for a few decades. However, the past two decades or so have seen a rise in ground water bringing salts to the crop root zone, leading to decline in crop productivity and even abandoning of cultivation. According to Kumar (2004), this introduction of canal irrigation has resulted in a chain of adverse social, agricultural, hydrological and environmental changes in south western Haryana with the inland basin as its epicenter. The conventional techniques of surface and sub-surface drainage utilized to remediate water logging can be effective in combating this problem. However, such drainage systems are costly to install, need periodic maintenance and have the associated environmental problem of production of large volumes of saline effluent. Universally, there are several examples where disposal of drainage effluent has created serious environmental problems (Ritzema *et al.*, 2008).

It has been established that vegetation in general and trees in particular act as biological pumps that can transpire copious amount of soil water into the atmosphere. The root depth of herbaceous vegetation is limited to a maximum of about 1-2 m in the soil

surface and has little or no contact with the aquifer waters. On the other hand, trees in general have a surface root system as well as a deep sinker root system. When soil moisture is available in the top layers, trees may utilize the surface moisture, like the herbaceous plants. When the surface soil water gets depleted, the shallow rooted herbaceous vegetation perishes. However, trees continue to thrive by drawing water from the aquifers which may be 5 to 20 m deep. In this process, they deplete or discharge the ground water table. The ground water table is recharged through the seepage of precipitated and/or irrigated water. If recharge is greater than discharge, a rise of water table occurs, over a period of time and vice-versa results in falling down of the water table. In majority of the pristine ecosystems, the above ground vegetation has had been in steady state equilibrium with both the surface and aquifer waters (Poore and Fries, 1985; Teskey and Sheriff, 1996; Packham *et al.*, 2001). However, as elaborated in the first paragraph of this chapter, the problem of water logging in some agro-ecosystems has occurred due to excessive recharge of the ground water table due to seepage of the liberally used irrigation water. It has been demonstrated that under ideal conditions, a tree canopy may lower water tables by 1-2 m over a time period of 3-5 years (Heuperman *et al.*, 2002; Kapoor, 2002). In the past decade or so, biodrainage, or the lowering of water table through evapotranspiration by strategically planted trees, has caught the fancy of the techno-scientific community as a drainage technique in irrigated agriculture (Kapoor, 2002; Ram *et al.*, 2002; INCID, 2003; Angrish *et al.*, 2006; Toky *et al.*, 2010). Kapoor (2002) opined that biodrainage can be a feasible option for controlling water logging and salinity in irrigated lands. Its additional advantages are economic cost and environmental friendliness.

Angrish *et al.* (2006) noted that comparative information on the consumptive water use potential or 'biodrainage potential' of different tree species is imperative. For example, an area which is chronically waterlogged 'fast biodrainers' are needed. On the other hand, in regions where the groundwater is sweet and is subjected to over exploitation for irrigation and other purposes water table is under constant decline. North Haryana again is a classical example of this situation where fresh ground water is more than 150 to 200 feet deep and the districts of Karnal, Kurukshetra, Ambala and Kaithal have been declared as "dark zones" (Kumar, 2004; Anonymous, 2009). In these areas monoculture of 'fast biodrainer' species like *Eucalyptus* might be adding to the ecological disaster by further contributing to the decline in water table. Here the use of 'slow biodrainers' in forestry and agroforestry systems is recommended. However, a comparative knowledge of the biodrainage potential of different tree species is highly inadequate.

Wullschleger *et al.* (1998) reviewed about 52 studies of whole plant water use in trees and concluded that weighing lysimeters, large tree potometers, ventilated chambers, radioisotopes, stable isotopes and an array of heat balance/heat dissipation methods had been used to provide quantitative estimate of whole tree water use. All these techniques have their own advantages and disadvantages. According to Meißner *et al.* (2010) lysimeters are most reliable and accurate for *in situ* water and solute flux assessment. For attaining reliable data about quality and quantity of seepage water the large weighing outdoor lysimeter is the best method but it involves significant investment and additional expenses for maintenance. In order to solve these problems, new need-based methods for the vertical collection of large volume soil monoliths and the placement of the soil monoliths in a container lysimeter unit, have been developed. Drainage type lysimeter are also in use where the influx and efflux of water is measured and no weighing infrastructure is needed (Boman *et al.*, 2007). Results obtained from these lysimetric studies form vital database for scaling up of results obtained with small-scale experiments to larger geographical areas.

From physiological point of view, the data of comparative tree water use would be worthwhile only if correlated with different physiological parameters or ‘biodrainage traits’. Most important amongst these are: leaf area, leaf orientation, transpiration rates, stomatal conductance, relative water content, leaf water retention and potometric water loss, sap wood properties, root characteristics etc. Further simultaneous consideration of abiotic factors such as temperature, actual vapor pressure, relative humidity, wind speed, sunshine hours, radiation and potential evaporation are cardinal (Wullschleger *et al.*, 1998; Landsburg, 1986; Larcher, 2002; Kallarackal and Somen, 2008; Pallardy, 2008).

The present study forms a part of the project “Ecophysiology of tree species to evaluate the biodrainage potential for water logged soils of Haryana” funded by Indian National Committee on Irrigation and Drainage (Ministry of Water Resources), Government of India, in which field plantations of different trees have been raised in waterlogged areas for measurement of their comparative biodrainage potential. The lysimeter based tree water use data and data on related physiological vis-a-vis meteorological factors shall be of paramount importance for scaling up, interpretation and modeling of the field results.

It is with this background in mind, the present lysimetric studies were therefore conducted with the following objectives:

1. To quantify biodrainage potential of different tree species.
2. To study different physiological traits of tree species grown in lysimeters.

Relevant reports in the literature along with theoretical concepts that have a bearing on the subject matter of this thesis are reviewed in this chapter under appropriate headings.

2.1 WATER USE BY VEGETATION AND BIODRAINAGE

2.1.1 Tree water use

The elaborately displayed leaf shoot system of the tree loses water into the ambient air. This water has to be replenished from the soil. Thus water uptake, its conduction to the shoot system and its ultimate loss from the transpiring surfaces is a dynamically linked process in “water balance.” The driving force for evaporation from any surface is crucially linked to the vapor pressure deficit between the surface and air and this holds good for leaves and other exposed surfaces of the tree as well. As the shoot is exposed to the vapor pressure deficit of the air, i.e. to a lower water potential, a flow of water is set in motion despite the water transfer resistance in homoiohydric plants. This potential difference in the soil-plant-atmosphere-continuum is the driving force for water transport through the plant (Schulze, 1986; Nobel, 1991; Larcher, 2002).

It is necessary to quantify tree water use both for the tree physiologist and forest hydrologist. Tree physiologists correlate tree water use information with more subtle processes like leaf area, stomatal conductance, leaf water potential, sap wood properties and overall hydraulic conductance of trees (Wullschleger *et al.*, 1998). More intensive studies pertain to gain insights into estimates of water use to partition the control of canopy transpiration between stomatal and boundary layer conductance (Hinckley *et al.*, 1994; Meinzer *et al.*, 1995) and to access the radial pattern of xylem water flux in non diffuse and ring porous species (Phillips *et al.*, 1996). Forest hydrologists use such information to i) help in resolving the issue of water resource management (Schiller and Cohen, 1995; Loustau *et al.*, 1996), ii) to evaluate the role of transpiration in forest and woodland hydrology (Barett *et al.*, 1996) and iii) to quantify the water requirements of short rotation forests (Cienciala and Lindroth, 1995; Lindroth *et al.*, 1995). Further, in agroforestry landscapes the tree versus crop trade off is, inter alia, linked with tree water use as well (Lafroy and Stirzaker, 1999; Dunin and Greenwood, 1986).

In an exhaustive review, Wullschleger *et al.* (1998) enumerated, data from 52 studies in which weighing lysimeters, large tree potometers, ventilated chambers,

radio isotopes, stable isotopes or thermal techniques were used to provide quantitative estimates of whole plant water use for trees growing in stands or plantations. Their survey included estimates of water use for 67 species spread over 35 genera. The quantitative rate of water use ranged from 10 kg/day for trees in a 32 year old stand of *Quercus petraea* in eastern France (Breda *et al.*, 1993) to 1,180 kg/day for a large over storey *Euphorbia purpuria* tree in the Amazonian rainforest (Jordan and Kline, 1977). Only three of the 52 studies reported whole tree rates of water use greater than 400 kg/day (Kline *et al.*, 1976; Jordan and Kline, 1977; Eermak *et al.*, 1982). Majority of observations (83 out of 92) indicated rates of water use between 10 to 200 kg/day for trees that averaged 21 m in height.

2.1.2 Biodrainage

The concept of biological drainage or biodrainage appears to have originated as a supplementary technology for the water logged agricultural areas where the conventional techniques of surface and subsurface drainage were needed or being partially practised. According to an International Programme for Technology and Research in Irrigation and Drainage (IPTRID) document (Heuperman *et al.*, 2002), the first documented use of term 'biodrainage' can be attributed to Gafni (1994). As also pointed out in the Introduction chapter of this thesis, the vertical drainage of water table through evapotranspiration of strategically planted vegetation particularly deep rooted trees is known as biodrainage. Trees as plantations along the canal banks, in fields as agroforestry components and as commercial block plantations have had always been a common sight. Their contribution as simple biological pumps cannot be disputed. It is the strategic component of their plantation that revolves around the concept of biodrainage (Angrish *et al.*, 2008).

The common strategies adopted in waterlogged agricultural landscapes are block plantations and strip plantations. The block plantations comprise of woodlots or blocks of suitable trees planted amidst a waterlogged area. The block plantation drawn ground water causes a 'cone of water table depression' underneath. However, the spacial extent of lowering of groundwater table around the surrounding recharge area has been shown to vary from 40 m (RIRDC, 1999) to even 730 m (Ram *et al.*, 2007). The vast differences may be attributed to the size and other characteristics of the discharge plantation block, hydraulic conductivity of the soil and cropping pattern. Discharge areas are often confined to saline or degraded areas so that less arable land is lost in the form of block biodrainage plantations (Archibald *et al.*, 2006).

Block plantations work well but these are not feasible where land holdings are small and fragmented, and blocks of land exclusively for biodrainage may not be

spared by the farmers. Here strip plantations on field bunds are the only alternative. In many Indian states, including Haryana, the standard unit of land with field bunds on all its four sides is an acre (0.4 ha) of about 66 m length in the east-west direction and 60 m width in north-south direction. Therefore, parallel strip biodrainage plantations in north-south direction of 66 m apart and with two rows of trees on each strip of about 0.5 m raised ridges are recommended (Ram *et al.*, 2007; Toky *et al.*, 2010). This agroforestry model has been successfully tested on a pilot scale around village Putthi, district, Hisar in Haryana and is considered as best option from the point of view of i) technology adoption by the farming community ii) lowering of water table to about 1 m over a period of 5 years and iii) remuneration to the farmers as timber.

The potential and practice of biodrainage has been realized worldwide. Thus, location specific biodrainage strategies have been variously integrated with the disturbed agro ecosystems in Australia (Heuperman, 1995; Heuperman, 1999; Lafroy and Stirzaker, 1999; RIRDC, 1999; Crosbie *et al.*, 2008), China (Zhao *et al.*, 2004), India (Kapoor, 2002; Ram *et al.*, 2007), Israel (Gafni and Zohar, 2001), Pakistan (Chaudhary *et al.*, 2000) and Uzbekistan (Khamzina, 2006 a, b).

2.2 LYSIMETRIC STUDIES

2.2.1 Types of lysimeters

Lysimeters are devices where several cubic meters of soil is encapsulated in a container with arrangement to monitor water flux into the atmosphere or to the water table formed at the container floor. The common feature of all lysimetric designs is that the root-soil zone of the experimental vegetation is completely cut off from the ambient soil with regard to any water or nutrient flux. At the same time, the atmospheric conditions and soil surface are almost comparable with natural conditions. A review of literature reveals that basically two types of lysimetric techniques are prevalent. These are i) Weighing lysimeters (Unlu *et al.*, 2010) and ii) Drainage lysimeters (Meißner *et al.*, 2010). In simplest version of weighing lysimeters, the potted plant method can be used. This is probably the best approach if the plant is small. However, for large plants or group of plants forming a canopy large container lysimeters have to be used. This method is expensive, but accurate data can be obtained. A cheaper modification is to place lysimeter on large plastic bag filled with fluid (water antifreeze) which extends into a side pipe at the surface. In the pipe, the level of liquid is measured by the weight of lysimeter and so it changes with water content of the soil in the lysimeter (Fritschen *et al.*, 1973; Salisbury and Ross; 1974; Edwards, 1986). The second type of lysimeter is drainage lysimeter. Here, drainage of water is measured using a soil embedded lysimetric

system. 'Drainage' means both water added and removed from the lysimetric system (Aboukhaled *et al.*, 1982; Meißner *et al.*, 2008; Gee *et al.*, 2009; Meißner *et al.*, 2010). An interesting study for the growth evapotranspiration and nitrogen leaching from young orange trees is by Boman *et al.* (2007). Here, 2.3 m³ polyethene tanks were used as lysimeters. A system of automated PVC pipes, pumps, float switches and flow meters maintained the desired level of water while measuring the water, input and water with leached nitrogen output. Earlier, Chhabra and Thakur (1998) used RCC lysimeters of 1.2 m diameter and 2.5 m depth filled with sandy loam alluvial soil, with provision to maintain water table depth at 1, 1.5 and 2 m from the surface and ground water salinity at 0.4, 3, 6, 9 and 12 dS m⁻¹. The water biodrained by *Eucalyptus tereticornis* and *Bambusa arundinacea* at the given water table depths and ground water salinity levels was monitored over four years by daily measuring the water needed for maintaining the water table. The trees absorb and transpire water throughout the year however, the capacity was more in summer and rainy than the winter season. The *Eucalyptus* plant could biodeplete 2880, 5499, 5518 and 5148 mm of water in first, second, third and fourth year of study period, respectively, from non-saline ground water and at a water table depth of 1.5 m.

2.2.2 Lysimeters as tools in quantification of tree water use

In view of the problems, faced in the exact quantification of water use, a plethora of workers have used lysimeters for different experimental purposes. A recent survey reveals that there has been a gradual rise in publications using lysimeters for a variety of hydrological applications. Meißner *et al.* (2010) showed that there is an increasing interest of plant scientists for using lysimeters as experimental tools. Since 1990, to date approximately 1,747 articles using lysimeters have been published. While the number of such publications was only 32 in 1991, it was 126 in 2007, 131 in 2008 and 147 in 2009. Lysimeters not only function as nearly *in situ* water and solute quality assigning tools but are of significant importance in a variety of fields such as agriculture management, meteorology, agronomy, environment and ecosystems, environmental pollution, applied geochemistry, environmental radioactivity, forest ecology and management, hydrology, forest meteorology, soil and tillage research, soil biology and biochemistry waste management and water quality management (Table 2.1). Such monitoring of water and solute fluxes in near *in situ* conditions is vital because the information is of basic interest to answer both practical and scientific questions regarding environmental protection of water resources, sustainable management of area under forest and agriculture mining or industrial areas, reducing leachate loss, landfills or exploring the fate of environmentally harmful substances.

Table 2.1: Representative lysimeter-based studies in different fields of silviculture, agriculture and environment.

	Lysimeter applications	Reference
1	Effect of drought on applied nitrogen	Dowdell and Webster, 1984
2.	The relationship of interception and forests	Dunin <i>et al.</i> , 1988; Crockford and Richardson, 1990
3.	Weighing lysimeter	Reyenga <i>et al.</i> , 1988
4.	Water use by cultivated willow	Grip <i>et al.</i> , 1989
5.	Effect of agricultural chemical management on fertilizer losses	Baker, 1990
6.	Partitioning of rainfall and canopy storage	Crockford and Richardson, 1990
7.	Denitrification and nitrate leaching	Bakar <i>et al.</i> , 1994
8.	Transport of solutes	Mallants <i>et al.</i> , 1996; Meißner <i>et al.</i> , 2000
9.	Soil water balance models	Struthers <i>et al.</i> , 2003; Wegehenkel <i>et al.</i> , 2008.
10.	Nitrogen use efficiency	Noulas <i>et al.</i> , 2004; Boman <i>et al.</i> , 2007
11.	Performance of different genotypes under field conditions	Noulas <i>et al.</i> , 2004
12.	Effect on growth, evapotranspiration and nitrogen leaching on trees	Boman <i>et al.</i> , 2007
13.	Hydrological and salinity impacts of biodrainage	Gafni and Zohar, 2008; Chhabra and Thakur, 1998

However, the major constraints of lysimetric studies are: i) the limited soil volume of the lysimeter container becomes a constraint for unimpeded growth of the tree root system and ii) huge expenditure involved in the construction and maintenance of such equipment.

2.3 TREE WATER USE PARAMETERS AND FACTORS

2.3.1 Leaf area

Leaf area is the most cardinal component of tree both as an ecophysiological measure of the photosynthetic and transpiration surface within a canopy. For a variety of experimental purposes, the values of leaf area *per se* are important. However, when there is intra- or inter-species leaf canopy interaction, the quantification of leaf area index becomes imperative.

2.3.1.1 Leaf area measurements

Measurement of leaf area is important and is done by direct or indirect methods (Norman and Campbell, 1989). The most straight forward direct method is destructive sampling of tree leaves or systematic collection of leaf litter and measurement of their area. Another approach is the use of allometric equations which are based on the correlation of parameters like girth at breast height and tree leaf area. The tree leaf area has first to be determined using destructive sampling and an allometric equation is derived, which is applicable to specific canopies (Chave *et al.*, 2005). Most of direct sampling techniques involve destructive sampling which is laborious and time consuming.

Presently, available indirect leaf area/leaf area index measurement techniques are simple, cheap, non destructive and can be quickly used over large areas. These take into account the fact that on its way through the plant canopy radiation must pass through successive layers of leaves. During this process, its intensity decreases almost exponentially with increasing amount of cover, in accordance with the Lambert-Beer Extinction Law. If there is homogeneous layering of foliage, the decrease in radiation can be computed from Monsi and Saeki's modification (Monsi and Saeki, 1953) of the extinction equation,

$$I_z = I_0 \cdot e^{-k \cdot LAI}$$

Here I_z , is the intensity of radiation at a certain depth from the top of the plant canopy; I_0 is radiation incident at the top of canopy; k is the extinction coefficient for this particular plant community; LAI is total leaf area above the level at which I_z is estimated, per unit ground area (the cumulative LAI). This concept has developed into the techniques of digital hemispherical photography for trees, which is used in studying canopy architecture using photographs taken looking upward through an extreme wide angle 'fish eye' lens. Hemispherical photographs capture the light obstruction/penetration patterns in the canopy, from which the canopy architecture and foliage area can be quantified (Broadhead *et al.*, 2003; Zhang *et al.*, 2005; Khabba *et al.*, 2009; Gonsamo *et al.*, 2010). There is scope of error in hemispherical image leaf measurement techniques if due precautions are not taken. Researchers have called for a standardized protocol for exposure settings for acquiring hemispherical photographs for uniformity of results (Jonckheere *et al.*, 2004).

2.3.1.2 Physiological significance of leaf area

Most woody plants produce copious amounts of foliage. Dale (1992) estimated that one hectare of forest land may have up to 20 ha of leaf area. Kozlowski *et al.* (1991) noted that as a forest grows its leaf area index increases to a

maximum and then either stabilizes or decreases. The higher leaf area index values (up to 20) of conifers over those of deciduous forest stands (3 to 6) are associated with slow growth and long leaf life spans, as well as later development of maximum leaf area index in conifer stands. Conifer stands typically achieve maximum leaf area index in 25 to 40 years in temperate zone as compared to five years in some deciduous forests (Bond, 1989; Woodward, 1995). Leaf area has a paramount effect on soil moisture content due to effects on water uptake, transpiration and soil evaporation (Ong *et al.*, 1991; Howard *et al.*, 1995). Teskey and Sheriff (1996) showed that for trees of *Pinus radiata* having a leaf area range from 83 to 337 m² showed many fold increase in daily water use, but transpiration per unit leaf area remained nearly the same. Radersma *et al.* (2006) showed that doubling of leaf area of *Cedrella serrata* and *Grevillea robusta* doubled water use when the leaf area was in the range of 1 to 11 m²/tree. These overall results showed that water use of tree lines was dependent on leaf area and transpiration rate per unit leaf area than by micro-meteorological factors.

2.3.2 Stomatal characteristics

Plant stomata, the vital gate between plant and atmosphere play a central role in plant/vegetation responses to environmental conditions which have been and are being investigated from molecular and whole plant perspectives, as well as at ecosystem and global levels (Nilson and Asmann, 2007). The leaf conductance for water vapor increases linearly with the degree of opening of the stomata. The maximal stomatal conductance is determined by anatomical features such as the size, structure, arrangement and density of the stomata of the plants concerned (species, variety, provenance, even individuals) and is thus a specific parameter for maximal transpiration. Crop plants and heliophytes have a particularly high diffusion conductance (300-500 mmol m⁻² s⁻¹), the maximal values for grasses lie between 250-400 mmol m⁻² s⁻¹, for broadleaved trees and shrubs between 160-250 mmol m⁻² s⁻¹, and the lowest conductance are those of succulent leaves (about 100 mmol m⁻² s⁻¹) (Korner, 1993).

Taking into account few of the relevant stomatal characteristics, Park and Furkawa (1999) found that the tropical rainforest species, *Pongamia pinnata* was more sensitive to the leaf to air vapor pressure difference and had higher stomatal density as compared to species like *Viburnum awabuki* and *Daphniphyllum macropodum*. Saadu *et al.* (2009) reported that species with the density range of 16-21 stomata per square millimeter namely *Caladium hortulanum* and *Manihot esculenta* were the least transpiring, as compared to *Colocasia esculenta* and *Ipomoea batatas* with stomata density range of 22-26 stomata per square millimeter

which were the most transpiring. Bobich *et al.* (2010) presented that during drought *Populus deltoides* trees growing in elevated CO₂ (800 $\mu\text{mol mol}^{-1}$) would have a lower volume flux density of water, stomatal conductance and transpiration per unit leaf area, as well as lower stomatal density and a greater stomatal response to drought and changes in vapor pressure deficit than would trees in ambient CO₂ (400 $\mu\text{mol mol}^{-1}$).

However, Jarvis and McNaughton (1986) cautioned that while on the one hand, plant physiologists and ecologists hold that stomata play an important dominant role in regulating the amount of water transpired by vegetation; on other hand, the micro-meteorologists nearly discard the role of stomatal properties in the process of transpiration. A wide range of potential evaporation formulae was taken for estimating evaporation from vegetation (Penman, 1948; Priestley and Taylor, 1972).

2.3.3 Sapwood characteristics

In the tree system, xylem is a highly specialized tissue, which is designed for hydraulic transport efficiency, mechanical strength and safety that allows tree like plants to have their characteristics expanse (Pallardy, 2008; Amritphale and Sharma, 2010).

In the literature collective length of vessel elements forming a conduit or vessel is taken into account rather than individual vessel element itself. Zimmermann and Jeje (1981) found that length of individual vessel members is negatively correlated with vessel diameter. The large diameter early wood vessels of ring-porous trees often are many meters long and may be as long as the stem is high. It is also reported that lianas have widest diameter and longest vessel up to 8 m long or more (Ewers, 1985). According to Zimmermann (1983) each woody plant has range of vessel length and much higher proportion of short than long vessels. Conversely, tracheids are individual cells having smaller diameter. Vascular tracheids are imperforate cells resembling small vessel member in form and position (Pallardy, 2008). Similar trends are obvious from more recent studies (Willigen *et al.*, 2000; Brodribb and Holbrook, 2005; Sperry *et al.*, 2006; England and Attiwill, 2007; Amritphale and Sharma, 2010).

Larcher (2002) listed reports to show that specific hydraulic conductivity ($\text{cm}^2 \text{s}^{-1} \text{MPa}^{-1}$) of conifer wood is 5-10, evergreen broadleaved trees with microporous wood is 3-15, deciduous broadleaved trees with microporous wood is 18-50 and liana wood is 300-500. Furthermore, the values of maximum velocity of sap flow (m h^{-1}) was found to be 1-2 in conifers, 1.5-3 in sclerophyllous woody

plants, 18-34 in broadleaved trees of humid tropical forests, 1-4 in deciduous broadleaved trees with microporous woody plants and 150 in lianas.

2.3.4 Tree potometry

In classical plant physiology, potometry refers to the measurement of the transpiration water used by a freshly cut stem, immersed in a water container, carefully avoiding cavitation of the cut stem. Potometric approaches involve not only cut branches but also entire main tree trunks to quantify whole tree water use (Salisbury and Ross, 1974; Roberts, 1977; 1978). Vertessy *et al.* (1997) validated the sap flow technique in *Eucalyptus regans* used by them by comparing the sap flow estimates with actual uptake of water by the tree from the reservoir of a potometric system. Gutierrez and Santiago (2006) found that water loss of about 16 L/day in *Ochroma lagopus* (balsa) and about 11.5 L/day correlated closely with heat dissipation technique based estimations. Campoe *et al.* (2010) also used whole tree potometers for validating sap flow measurements and a three dimensional MAESTRA model of individual tree transpiration in *Eucalyptus* plantations. The advantage of measurement of potometric water loss as a water transport or biodrainage trait is, therefore, obvious.

2.3.5 Root characteristics

Trees have an integrated modular architecture of which roots are the dynamic “hidden half” and their role in biodrainage is vital. Tree roots are wonderfully opportunistic in their search for water and nutrients and follow moisture gradients up to 20 m horizontally or even vertically downwards (Knight, 1999). *Eucalyptus* roots are dimorphic with most of the roots remaining confined to about 1 m above the soil. Beneath this a well developed sinker root system may penetrate down to the water table up to 15-20 m below the soil surface. Ram *et al.* (2007) reported 4.40 m deep sinker roots logged on with water table in a 20 year old *Eucalyptus tereticornis* plantation in Rohtak. Toky and Bisht (1992) excavated the root systems of 12 species of 6 years old trees of north-western India and found that while all species had most of their roots in the top soil upto 50 cm, roots of *E. tereticornis* reached the depth of 2.3 m. In lysimetric studies however, the root growth may get restricted due to limited space and conclusion regarding their functional role is limited to transpiration water loss only.

2.3.6 Environmental factors and tree water use

According to Pallardy (2008), transpiration is predominantly affected by light intensity, vapor concentration gradient between leaf and air, wind speed and soil water supply. Both light duration (sunshine hours) and intensity (photon flux density) over a region affect its temperature. Strong irradiation warms the leaf

surface and thus leads to steeper vapor pressure and transpiration. It is reported in classical literature that, in Nebraska (Weaver and Mogensen, 1919) and Leningrad (Ivanov, 1924) winter transpiration of conifers was less than 1% of summer rate. Zepel *et al.* (2006) reported that an evergreen *Callitris/Eucalyptus* woodland in southeast Australia showed minimal (<1 mm/day) transpiration rates during winter as compared to very high (>3.5 mm/day) in summer. Even in some parts of the tropics, seasonal cycles in transpiration occur because of variations in rainfall, humidity and soil moisture. For example, Ringoet (1952) found large seasonal differences in transpiration of oil palms growing in the Belgian Congo.

On the whole, straight forward consideration of factors like temperature, vapor pressure and relative humidity on transpiration is tricky as they have a complex interaction amongst each other. Vapor pressure deficit is a more useful way to express the vapor flow for transpiration as well as condensation. Vapor pressure deficit increases the transpiration demand indicating how much moisture from the plant tissue is transferred into the air. Conversely, very low vapor pressure deficit indicates closer proximity to dew point or condensation and minimal transpiration. Vapor pressure deficit is an improvement over relative humidity measurement alone because vapor pressure deficit takes into account the water holding capacity of the air which roughly doubles with every 11.4°C increase in temperature (Prenger and Ling, 2000). Therefore, consideration of vapor pressure deficit along with other parameters like transpiration, xylem sap flux, sapwood area, tree hydraulics, stomatal conductance, tree water use, water table etc. is prevalent (Oren *et al.*, 1999; Adelman *et al.*, 2008). Equally straight forward is consideration of potential evaporation or pan evaporation from a standard open pan (Allen *et al.*, 1998).

Wind is another cardinal factor affecting the tree water use. The resistance due to the layer of unstirred air next to the leaf surface through which water vapor must diffuse to reach the turbulent air of the atmosphere. This is called the leaf boundary layer resistance. The thickness of the boundary layer is determined primarily by wind speed. When the air surrounding the leaf is very still, the layer of unstirred air on the surface of the leaf may be so thick that it is the primary deterrent to water vapor loss from the leaf. Increases in stomatal apertures under such conditions have little effect on transpiration rate. When wind velocity is high, the moving air reduces the thickness of the boundary layer at the leaf surface, reducing the resistance of this layer. Under such conditions, the stomatal resistance will largely control water loss from the leaf. Various anatomical and morphological aspects of the leaf can influence the thickness of the boundary layer. Hairs on the surface of leaves can serve as microscopic windbreaks. Some plants have sunken

stomata that provide a sheltered region outside the stomatal pore. The size and shape of leaves also influences the way the wind sweeps across the leaf surface. Although, these and other factors may influence the boundary layer, they are not characteristics that can be altered on an hour-to-hour or even day-to-day basis (Grace, 1976; Roden and Pearcy, 1993; Taiz and Zeiger, 2006).

The present investigation entitled “**Lysimetric studies on some tree species to evaluate their biodrainage potential**” encompasses field as well as laboratory experimentations. The exact methodology is detailed below:

3.1 FABRICATION OF LYSIMETERS

A suitable lysimetric set up was established in the research Farm area adjacent to Ludas road of CCS Haryana Agricultural University, Hisar. A 35×45 m² plot from a field hitherto under pearl millet -wheat rotation was earmarked for this purpose. For each lysimeter commercially available plastic overhead water storage tanks of 3,000 L capacity were utilized after cutting their top lid. The left over cylindrical drum 1.25 m in height and 1.45 m in diameter (2.84 m³) was used as the mainframe of the lysimeter. A schematic diagram of the lysimeter design is given in Fig. 3.1. Cylindrical pits were dug in the soil (Fig. 3.2a) and the bottom of each pit compacted flat with a mixture of sand, gravel, and cement. The drums were lowered and placed on the flat platform with 10 cm of the drum projecting above the original soil surface, suitably filled up with the field soil (loamy sand typic haplustepts) (Fig. 3.2b). An ‘observation well’ was also installed in each lysimeter. For this a 1.30 m long and 8 cm diameter pipe was inserted vertically downwards up to the bottom of each lysimeter at a distance of 15 cm from the lysimeter wall. The lower 20 cm portion of the well pipe was drilled with 10 mm diameter perforations at a distance of 2×2 cm and tightly wrapped by two layers of a nylon mesh. The observed wells formed an excellent system to readily observe water table in each lysimeter correct by upto 1 mm. For this a sufficiently long thin disposable strip of non glossy brown paper clipped to a 75 g plumbline iron weight was used. The strip was gradually lowered into the well. When the plumb line just dipped in water the paper strip acquired a clear and distinct water mark line. The upper end of the strip at the level of well pipe was also marked with a pencil. The strip was taken out of the well and the water table depth measured as the distance (mm) between the pencil mark and water mark with the help of a flexible measuring tape. Further the well also served as conduit to add or drain out water directly to the water table of the lysimeter as per experimental requirements.

Edge to edge distance of the lysimeters was 3.60 m and centre to centre (plant to plant) distance was 5.0 m. The overall layout comprised of 24 lysimeters in 6 rows of 4 lysimeters each in east to west direction (Fig. 3.3). A boundary of 24

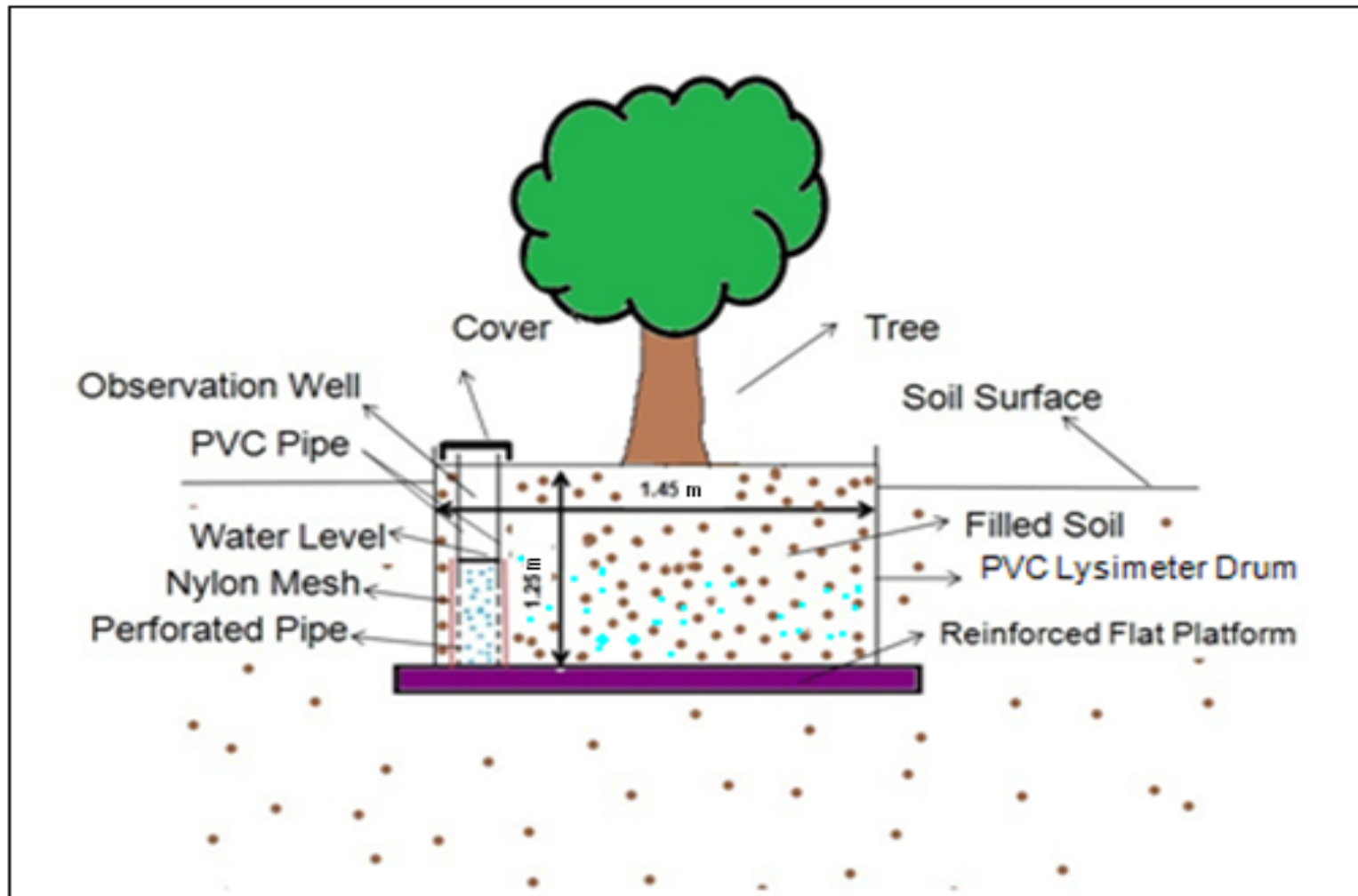


Fig. 3.1: A schematic diagram of the lysimeter setup (see text for details)



Fig. 3.2: (a) A cylindrical pit being dug for the fixation of lysimeter drum at the lysimeter site.

(b) A freshly installed lysimeter filled up with field soil. Note the circular rim of the drum projecting above the soil. Arrow points towards the observation well installed in the lysimeter.

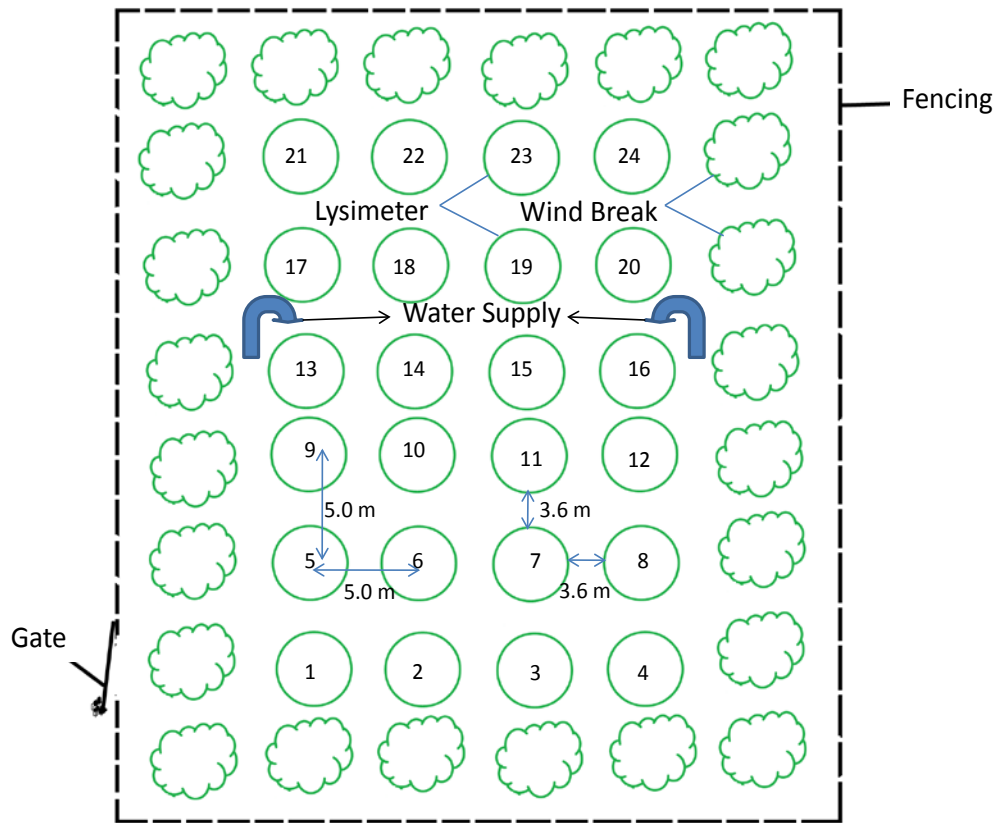


Fig. 3.3: Field layout of the lysimetric set up. Figures within the parenthesis denote lysimeter number of the species as in the figure above in a completely randomized design. The twenty four lysimeters were planted with *C. equisetifolia* (2,8,11,13), *E. tereticornis* C-10 (4,15,18,21), *M. azedarach* (7, 10, 16, 23), *P. juliflora* (3, 5, 12, 14), *T. arjuna* (6,9,19,24) and control (1, 17, 20, 22). Note that the lysimeters are surrounded by a wind break of *Tamarix aphylla* trees on all the four sides. A barbed wire fencing protected the plot.

Tamarix aphylla trees, each planted at a distance of 3.6 m from each lysimeter, was also established. This served as a wind break and moderator of the microclimate for the lysimetric area.

3.2 ESTABLISHMENT OF SEEDLINGS

Seedlings of five different tree species were raised or procured from different sources and maintained in a screen house of the Department of Botany and Plant Physiology, CCS Haryana Agricultural University (Fig. 3.4). These are:

- (1) *Casuarina equisetifolia* L. (Casuarina)
- (2) *Eucalyptus tereticornis* clone-10 Sm. (Eucalyptus/safeda)
- (3) *Melia azedarach* L. (Bakain)
- (4) *Prosopis juliflora* (Sw.) DC. (Mestique/vilayati kikar)
- (5) *Terminalia arjuna* (Roxb.) (Arjun)

The seedlings were initially sown/established in thick perforated polyethylene bags of suitable size containing loamy soil, Balsamand dune sand and farm yard manure in the ratio of 2:1:1. *C. equisetifolia* and *P. juliflora* were raised from seeds. For *P. juliflora* a single vigorous tree was earmarked and its seeds were collected and scarified with concentrated sulphuric acid and sown in the polythene bags. Seeds of *C. equisetifolia* were procured from Forest Tree Breeding Institute, Coimbatore and germinated to raise seedling in polybags. In case of *E. tereticornis* clone 10, *M. azedarach* and *T. arjuna* seedlings were procured from the Forest Department Haryana nursery and transferred to bigger perforated polythene bags as described above. These were allowed to grow under ambient conditions for about 1½ years.

3.3 ESTABLISHMENT OF SEEDLINGS IN LYSIMETER AND EXPERIMENTAL DESIGN

In mid July 2006, the one and half year old saplings were transplanted to lysimeters. The polythene bags were slit open and the root-soil cold was gently planted in the centre of each lysimeter. Four saplings (replicates) of each of the five species were planted in completely randomized design (CRD) in 20 lysimeters keeping another four lysimeters as blank controls (Fig. 3.3). Trees were surface irrigated as per requirement for the first 6 months. From February 2007 onwards irrigation was gradually directed through the bottom of the lysimeter through the observation well pipe.

A fertilizer of 100 g of urea and 100 g of KH_2PO_4 was applied annually in two split doses one each in 1st week of July and 1st week of February.



Fig. 3.4: Seedlings in the screen house of the Department of Botany and Plant Physiology, CCS Haryana Agricultural University.

3.4 CALIBRATION FOR MEASUREMENT OF TRANSPIRATION

For quantification of water transpired, water table fluctuation in the lysimeter was monitored. Measured amount of water could always be directly added to, or taken out from the water table. At the time of start of the experiment lysimetric soil was compacted to an average bulk density of 1.5 g/cm³. Necessary calibration was done by adding sufficient water to each observation well so as to maintain the water table at the depth of about 90 cm from surface. Twenty litres of water was added to each lysimeter through the observation well. Surface of each lysimeter was sealed immediately with thick polythene sheet to prevent any evaporation from the lysimeter soil surface. After 12 hours of equilibration the polythene cover was removed and water table level in each well was again recorded. It was found that for 20 liters of water added the water table increased by an average of 180 mm. Thus for every 1 liter addition/deletion of water the water table increased/decreased by a factor of 9 mm. This procedure was again repeated in the year 2007, in all the control lysimeters and results were found to be the same. This calibration provided a convenient and accurate method of measurement of water loss through evapotranspiration. Therefore, for all experimental measurements water table was adjusted to depth between 80-90 cm which was individually measured between 11.00 a.m. to 12.00 noon. The depth was again measured after 24 hours on the next day. The volume of water evapotranspired in liters was measured by multiplying the difference in the level of water tables multiplied by the calibration factor of 0.9. In tree species where predisposition of the evapotranspiration was expected to be around 40 liters or more, and the water table was likely to hit bottom of the lysimeter, measured amount of water was added beforehand after taking the initial reading. The added water volume was adjusted in the next day reading. By and large the rainfall was scanty and the rainfall water never filled up the drums and spilled over. Loss of water through evaporation (W_e) was measured from the control lysimeters which were without any trees but with water table between 80-90 cm like other lysimeters. Water evapotranspired (W_t) was measured in all the other lysimeters with trees by taking into account the difference in the water table at 24 hours interval. Water biodrained (W_b) by an individual tree in the lysimeter was calculated by subtracting water evaporated from water evapotranspired as per the following equation:

$$W_b = W_t - W_e$$

This procedure gave results that should be expected to be nearest to the exact, as water evaporated from the control lysimeters is likely to be more because

of lack of surface shading and increased soil temperature, less accumulation of litter etc. on the soil surface.

3.5 EXPERIMENT 1

To quantify lysimeter-based biodrainage potential of different tree species.

In this experiment different observations were made relating to the lysimeter-grown trees (as described above). Observations were mostly recorded at fortnightly intervals. Details are as follows:

3.5.1 Tree height, girth and DBH measurements

When transplanted in July 2006, the main stem of the plant was pruned to have a uniform height of about 45 cm. Subsequently the height was recorded at monthly intervals with the help of a meter scale. For taller trees clinometric readings using trigonometric functions was used. Girth at breast height (GBH) of the tree was measured with the help of a flexible tape at breast height (1.37 m above ground). In case of *P. juliflora* where two or three bold stems originated from the very ground level and contributed equally to the tree canopy, the tree girth was taken as the combined girth of all the major trunks at the breast height level. Diameter at breast height (DBH) was calculated from GBH using following the formula:

$$DBH = GBH \div 3.14$$

3.5.2 Leaf area (LA)

Leaf area was measured using Hemiview leaf area measurement system (version 2.1 Delta-T Devices, UK). For this a hemispherical image of the tree canopy was taken from the base of the tree crown, as close to the centre as possible, with the help of fish eye lens, fitted to camera system of the Hemiview instrument. The hemispherical image was edited in Adobe Photoshop by ignoring the areas dominated by tree trunks or other vegetation using an image editor (Fig. 3.5). The edited hemispherical image was fed to computer software supplied by the Delta-T Devices for the calculation of leaf area of single tree corresponding to the shape that best fits the tree. This interpreted the image for computation of leaf area using some subsequent calculations in Microsoft Excel solver, using “least squares” technique which calculated its best fit estimates for ELADP (Ellipsoidal leaf angle distribution parameters), LD (Leaf area density) and DLLAI (Drip line leaf area index) and give direct values for the tree leaf area.

3.5.3 Shoot extension and number of leaves

Extension growth of shoots and number of leaves produced on the branch during the annual growth cycle of the five lysimeter grown tree species was recorded. For this, twenty uniform and healthy branches in the top of lower one-

third portion of the tree were tagged in September 2008. The number of leaves and length of stem at this point of time as presented in Fig. 4.10a and b was taken as nil. Fortnightly readings of the increments in stem growth along with number of leaves were recorded for a period of one year.



Fig. 3.5: Hemispherical image of the tree canopy of *P. juliflora* (a) and its edited version in Adobe Photoshop (b) for computation of leaf area by software. Similar hemispherical image (c) and its edited version (d) for leaf area computation in *T. arjuna*.

3.5.4 Water biodrained (Wb)

As explained in section 3.4 (Calibration for measurement of transpiration) of this chapter Wb was computed by the equation as follows:

$$Wb = Wt - We$$

In all, fifty such data sets were recorded at fortnightly intervals (starting preferably 1st and 16th of each month) for a period of two years from August 2007 to

August 2009 as in Fig. 24 and elsewhere. The 1st observation on 1st August, 2007 is denoted as Aug 07(1). Likewise the 3rd, 4th, 5th observation dates are denoted as Sep 07(3), Sep 07(4), Oct 07(5) and so on in different figures.

3.5.5 Cumulative and average water biodrained:

The cumulative per year and average water biodrained per day (Fig. 4.20a, b) were computed mathematically from the different values of Wb obtained as above.

3.5.6 Average seasonal fluctuation:

Average seasonal fluctuation of Wb (Fig. 4.21) was calculated from mathematical mean of all the tree species starting observation number 1 to 50.

3.5.7 Meteorological data:

Meteorological data such as maximum and minimum temperature, morning and evening relative humidity, sunshine hours, actual vapor pressure, wind speed and potential (pan) evaporation etc. were collected from the observatory of the Department of Agricultural Meteorology, CCS Haryana Agricultural University, Hisar. The observatory is located at the University farm about 800 m away from the lysimeter site. Vapor pressure deficit (VPD) was also computed from the meteorological parameters of Avp and RH as follows:

$$\text{VPD} = \text{Saturated vapor pressure (Svp)} - \text{Avp}$$

$$\text{where, Svp} = (\text{Avp}/\text{RH}) \times 100$$

3.5.8 Statistical analysis:

Data of the present experiment was analyzed for Analysis of Variance by OP STAT Package available at the CCS Haryana Agricultural University, Hisar website (<http://www.hau.ernet.in>). Both the correlation and regression equations were obtained through statistics software SPSS (Statistical Package for Social Sciences) available in the Department of Bioinformatics of CCS Haryana Agricultural University, Hisar.

3.6 EXPERIMENT 2

To study different physiological traits of tree species grown in lysimeters

Observations on different physiological parameters were taken in four months representatives of major seasons i.e. April 08 (dry summer), July 08 (wet summer), October 08 (autumn) and January 09 (winter). The following observations were taken:

3.6.1 Transpiration rate

Transpiration rate ($\text{mmol m}^{-2} \text{ s}^{-1}$) was recorded 4 times by LCi compact portable photosynthesis system-ADC BioScientific Limited, UK.

Observations were taken 4 times i.e. in month of April, July, October and January.

For uniformity of leaf sample a healthy leafy shoot was earmarked from the lower one-third portion of the tree canopy towards the eastern sun-exposed side. One fully expanded healthy leaf was selected from this branch leaving 8-10 young leaves from the shoot tip*. This observation was taken in the morning in full sunlight around 11 a.m.

3.6.2 Stomatal conductance (g_s)

Stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$) was also obtained from LCi compact portable photosynthesis system-ADC BioScientific Limited, UK. Observations were taken 4 times and the fully expanded leaf was selected as described in section 3.6.1.

3.6.3 Relative water content (RWC)

The leaf samples were collected from the tree following the standard procedure and immediately shifted to polythene bags in an ice bucket and transported to the laboratory to avoid moisture loss. Leaf was weighed for fresh weight and immersed in distilled water in a Petri dish. After 6 hours leaf was removed from water, its surface was blotted off to remove surface water. Leaf was reweighed to obtain turgid weight. Subsequently leaf was dried in an oven at 70°C for 2 days and weighed to get dry weight. From these three weights, relative water content (%) was computed using the following equation given by Turner (1981):

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

3.6.4 Leaf water retention (LWR)

The leaf samples were collected from the tree following the standard procedure and immediately shifted to polythene bags and kept in an ice bucket for quick transport to the laboratory to avoid moisture loss. For determination of LWR slightly modified method of Clarke (1987) was followed. Thus each leaf was immediately weighed to obtain fresh weight. Thereafter it was placed in an incubator at 28°C at 50% relative humidity for 6 hours and weighed immediately thereafter. Subsequently the leaf was oven dried for 24 hours at 70°C to obtain its dry weight. Excised leaf water loss was computed by the formula:

$$\text{LWR} = \frac{\text{Fresh weight} - \text{Weight after 6 hour}}{\text{Fresh weight} - \text{Dry weight}} \times 100$$

3.6.5 Potometric water loss (PWL)

For determining potometric water loss (per unit leaf area or per unit dry weight) shoots were collected from the experimental site in between 3-4 p.m.

* This procedure was also followed for selecting fully expanded leaf for measurement of stomatal conductance, relative water content, leaf water retention and stomatal frequency as well.

Samples were collected from the trees in the form of 30-45 centimeter long twig. For sampling, a large (5 L) water filled plastic beaker was taken and raised adjacent to the twig. The twig was immersed in water and cut from the plant with the help of sharp secateurs. While cutting, precaution was taken to quickly cut the twig in one stroke under water in the beaker to avoid cavitation. The cut sample twigs were transported to laboratory quickly taking care to keep the cut ends immersed under water in the beaker. Four volumetric flasks for each species were taken in which known volume of water was added. Cut end of the twig was inserted in each flask. One set of volumetric flask containing only water but no twig was treated as control for this experiment. All flasks containing twig as well as blank set was kept in net house for 24 hours under ambient condition of temperature and relative humidity. After 24 hours, the decrease in volume of water was measured. Leaves were detached from the shoot and total leaf area was measured by CI-203 portable laser area meter (CID Inc., USA). Water loss was interpreted as ($\text{ml H}_2\text{O}/\text{cm}^2$ leaf area/day)

3.6.6 Stomatal frequency

Stomatal frequency was taken as the number of stomata per unit area on both surfaces of leaf. Fully expanded healthy leaves were excised as per the standard procedure. These were immediately plunged in to water. A one cell thick epidermal peel was made from the abaxial and adaxial surface of the leaf with a sharp razor blade. The peel was mounted on a microscope slide and cover slip and observed under a microscope. The number of stomata was counted in 10 randomly selected fields at 15X/40X of 3-4 leaves. Diameter of the field of view of microscope at that magnification was measured with a stage micrometer. Data was interpreted as number of stomata per unit leaf area on the abaxial, adaxial and average of abaxial and adaxial surfaces.

3.6.7 Tracheary elements

Length and width of tracheary elements i.e. tracheids and vessels, was determined by macerating the sap wood by Schultze's Method (Prakash, 1987). Sapwood was taken from the main trunk of each tree species about 1.3 m from the soil surface. About 4 cm square piece of bark was removed with the help of a sharp scalpel. The exposed wood was scooped out and preserved in FAA solution.

For maceration, small slice of wood material was taken in a china dish. Enough of 20 % HNO_3 was added to immerse the piece of wood. Few crystals of potassium chlorate were added to the HNO_3 and the material was heated gently until it was bleached white. A small sample was tested under the microscope. If the cells did not separate heating was continued further. The properly macerated material was

washed thoroughly in water and stained with safranin. Stained tissue was rinsed in water and dehydrated in alcohol series, cleared in xylol and mounted in DPX mount. The macerated tissue was viewed in microscope in 15X/10X. Length and width of tracheary elements i.e. tracheids and vessels were measured using ocular and stage micrometer.

3.6.8 Trade off with surrounding vegetation

The surrounding vegetation representing the above ground biomass of each tree in the lysimeter comprised of wild vegetation of which the grass *Cynodon dactylon* was the predominant component. Effect of various tree species on the surrounding vegetation was measured by harvesting the above ground biomass growing within the lysimeter. For this the ground vegetation was allowed to grow undisturbed, including the control lysimeters, for three months i.e. July 2009 to September 2009. Above ground biomass was harvested from a similarly placed area of 50 cm² quadrat towards the west from each lysimeter soil surface. The harvested biomass was sampled in paper bags, oven dried at 70°C for 48 h to obtain a constant weight. The data was interpreted on g/m² basis.

3.6.9 Statistical analysis and Correlation

As explained in the methodology of first experiment (3.5.8).

As also mentioned in Chapter III (Materials and Methods) of this thesis, the present experimentation comprises of two experiments. The first experiment deals with lysimetric measurement of the water biodrained and the associated tree growth and environmental factors affecting the biodrainage. Various morphophysiological parameters or 'traits' considered as vital components of the biodrainage phenomenon were studied in the second experiment. The results obtained supported by suitable figures and tables are detailed as follows:

4.1 EXPERIMENT

To quantify lysimeter-based biodrainage potential of different tree species.

4.1.1 Tree height

It may be noted at the outset that the plants raised in lysimeters were about 3 years and six months old towards August, 2007 and had attained tree like proportions when the results reported were recorded (Fig. 4.1 to 4.4). All these plants had completed their juvenile phase as these showed flowering and even fruit setting. The flowering time of different species was end March in *C. equisetifolia*, end May in *M. azedarach*, end February in *P. juliflora* and May in *T. arjuna*.

It is seen from results presented in Fig. 4.5 that, in general, tree height showed a gradual increase during the period of two years i.e. from August 2007 to August 2009. In *M. azedarach*, *P. juliflora* and *T. arjuna*, there was no increase in height during winter particularly during the months of December, January and February. Modest increase was observed during the months of April through September. On the other hand, in *C. equisetifolia* and *E. tereticornis* C-10, growth increments in height occurred throughout the year but were more pronounced during the months of August and September. Maximum tree height towards August 2009 was obtained by *E. tereticornis* C-10 (824 cm) followed by *C. equisetifolia* (690 cm), *P. juliflora* (374 cm), *T. arjuna* (291 cm) followed by *M. azedarach* (226 cm).

4.1.2 Girth (GBH) and diameter at breast height (DBH)

Again, like height, the data on the girth at breast height (GBH) and diameter at breast height (DBH) is presented here only for two year period August 2007 to August 2009, when the plants growing in lysimeter had developed tree-like proportions. The different lysimeter-grown tree species acquired thick boles from the base upwards (Fig. 4.6). The tree GBH showed a gradual increase for the two year period of experimentation under consideration (Fig. 4.7). However, girth



Fig. 4.1: Lysimeter grown tree of (a) *M. azaderach* and (b) *C. equisetifolia* in June 2009. White bar indicates 1 m. Note the height and expanse of *C. equisetifolia* was many fold more as compared to *M. azaderach*.

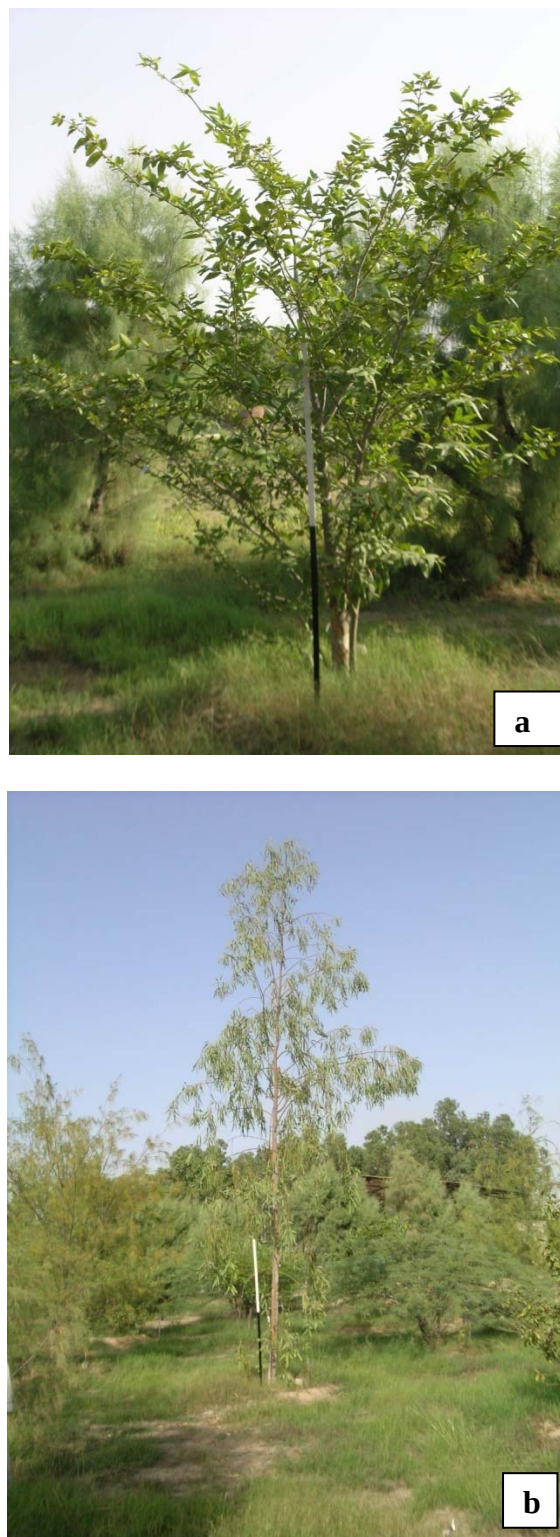


Fig. 4.2: Lysimeter grown tree of (a) *T. arjuna* and (b) *E. tereticornis* clone 10 in June 2009. White bar indicates 1 m. Note the height of *E. tereticornis* is manifold greater than *T. arjuna*.



Fig. 4.3: Lysimeter grown tree of *P. juliflora* in June 2009. White bar indicates 1 m. Note that in *P. juliflora* lateral expanse of the canopy is much more as compared to its height.

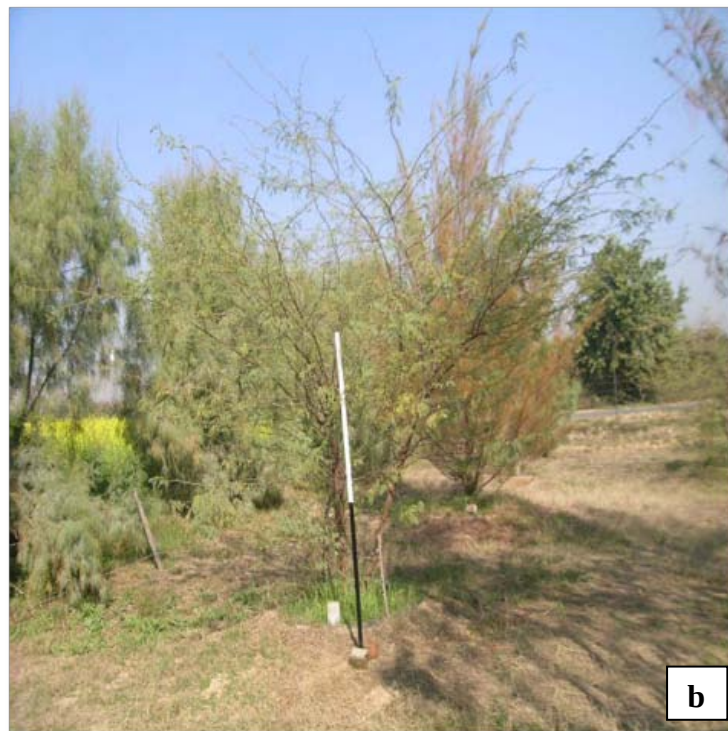


Fig. 4.4: (a) A close up view of lysimeter grown tree of *M. azadirach* in December 2008. Note the lack of foliage due to the winter deciduous nature of the tree. Red arrow shows the water supply system at the lysimeter site. White bar is equal to 1m.

(b) A close up view of lysimeter grown tree of *P. juliflora* in December 2008. Note sparse foliage due to shedding of leaves in winter.

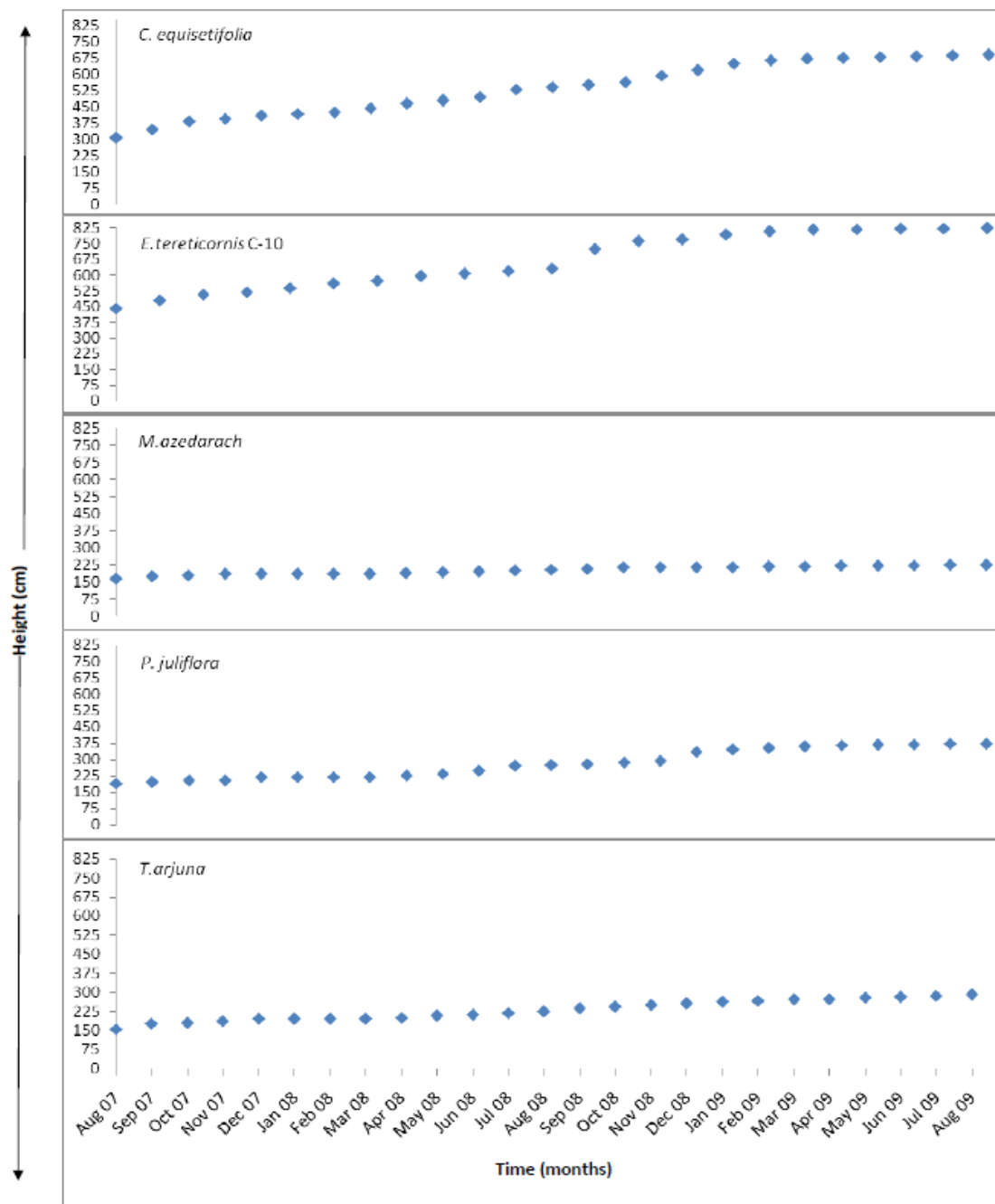


Fig. 4.5: Height (cm) of different tree species grown in lysimeter from August 2007 to August 2009. (CD at 5% = 9.15)

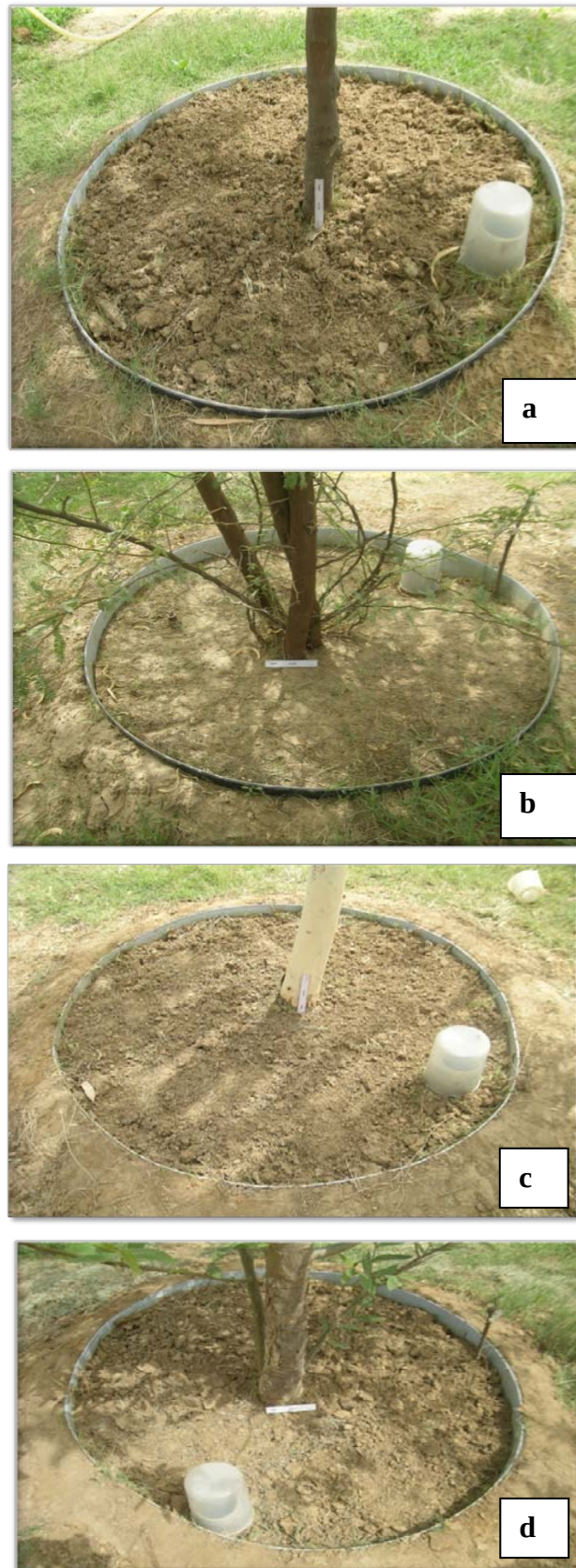


Fig. 4.6: A close up view of the basal trunk of the lysimeter-grown tree of (a) *Melia azadirach* (b) *Prosopis juliflora* (c) *Eucalytus tereticornis* C-10 (d) *Terminalia arjuna*. White bar is equal to 15 cm

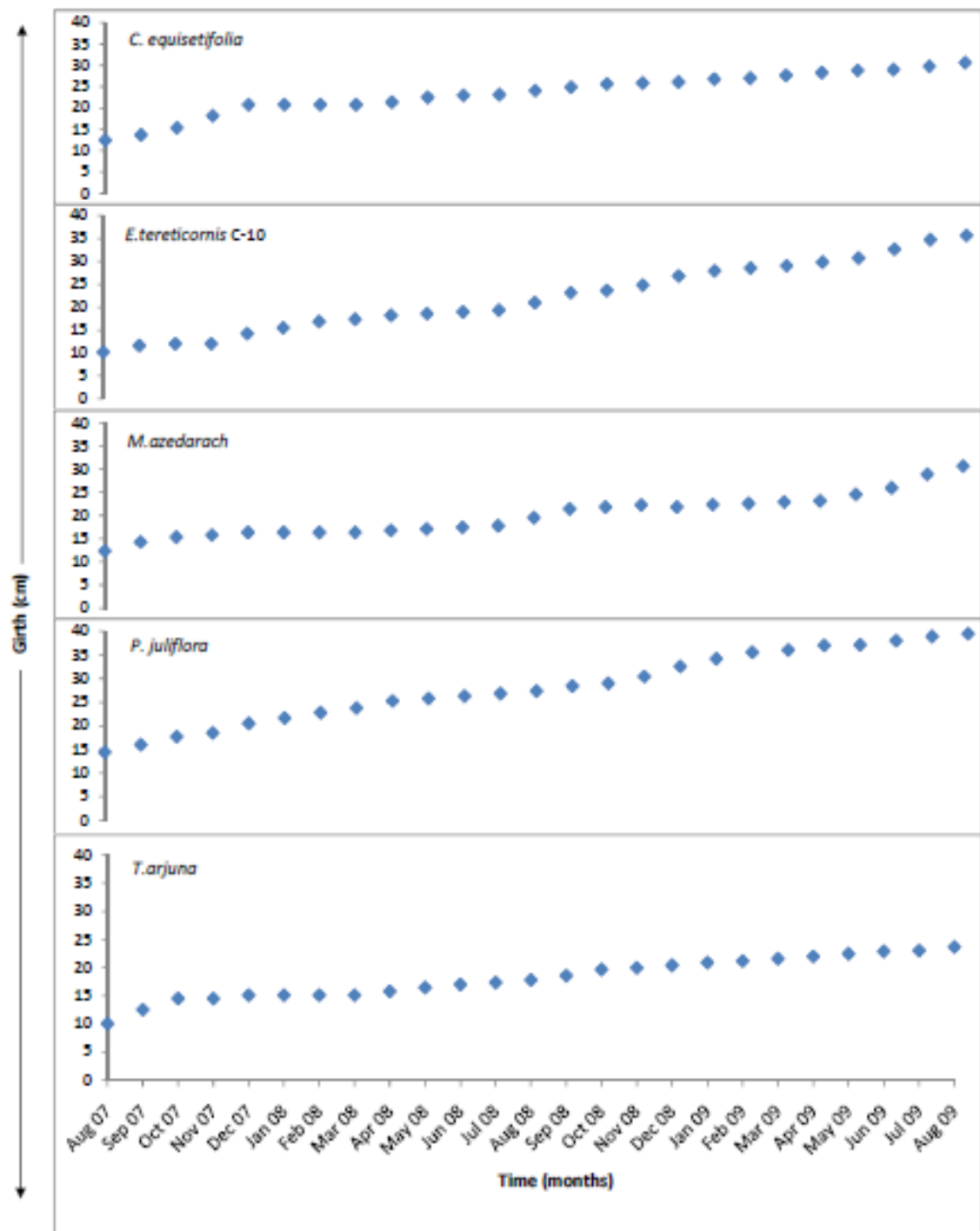


Fig. 4.7: Girth at breast height (GBH) (cm) of different lysimeter grown trees from August 2007 to August 2009. (CD at 5% = 0.79)

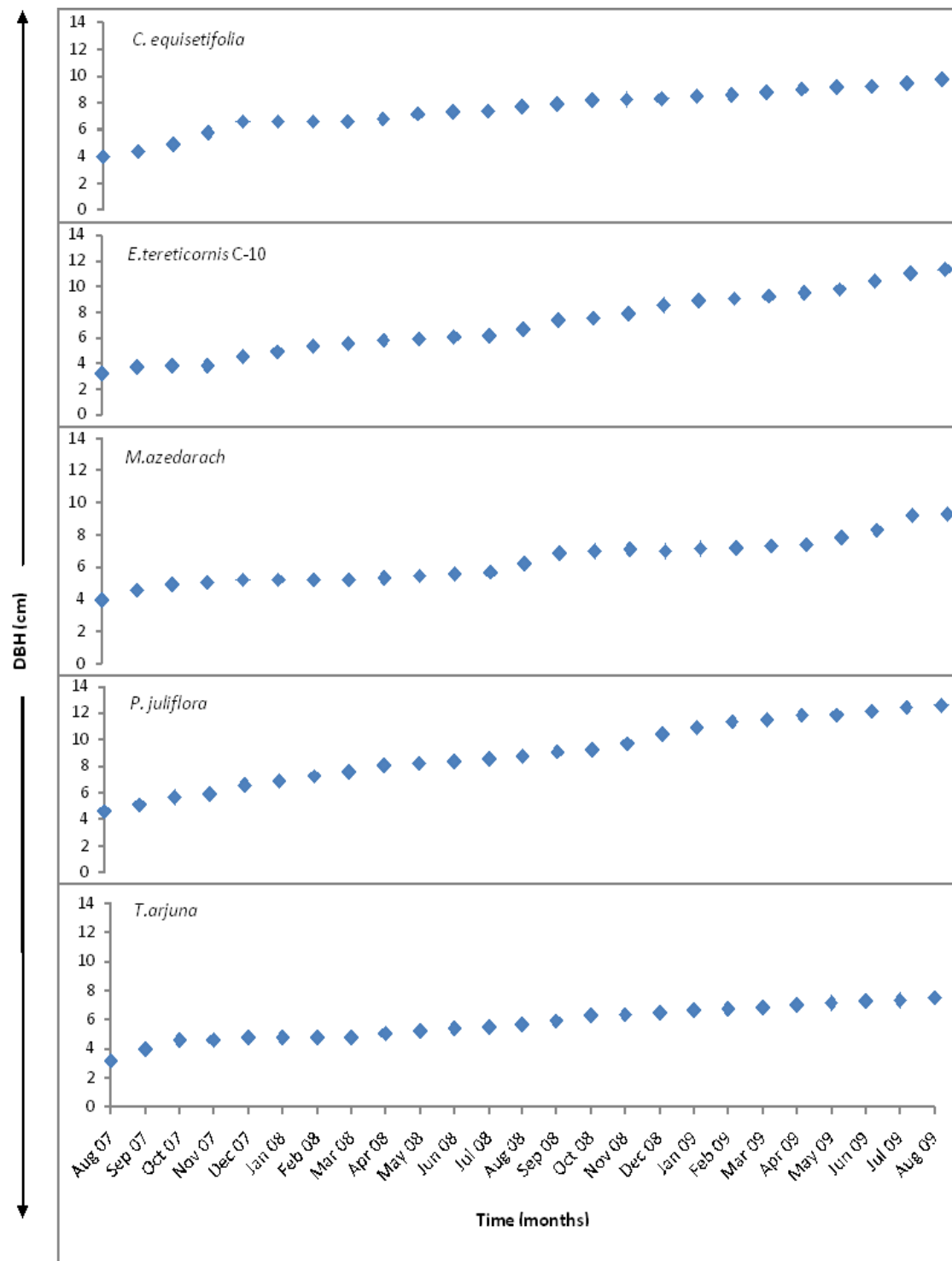


Fig.4.8: Diameter at breast height (DBH) (cm) of different lysimeter grown trees from August 2007 to August 2009. (CD at 5% = 0.31)

increments during the winter months of December, January and February were minimal particularly in *M. azedarach*, *P. juliflora* and *T. arjuna*. Towards August 2009, the maximum girth was depicted by *P. juliflora* (39 cm) followed by *E. tereticornis* C-10 (35 cm), *C. equisetifolia* (30 cm), *M. azedarach* (29 cm) and *T. arjuna* (23 cm). As expected the DBH values (Fig. 4.8) followed the same trend and the final values for different tree species in decreasing order were *P. juliflora* (12 cm), *E. tereticornis* C-10 (11 cm), *C. equisetifolia* (10 cm), *M. azedarach* (9 cm) and *T. arjuna* (7 cm).

4.1.3 Leaf area (LA)

Leaf area of the five tree species grown in lysimeter for a period of two years is presented in Fig. 4.9 for period of experimental observations during August 2007 to August 2009. It is seen that, in general, leaf area was more during the growth season 2008-2009 as compared to 2007-2008. Seasonal variations in leaf area were more interesting and are detailed below:

In *C. equisetifolia*, the leaf area ('leaves' in *C. equisetifolia* are actually modified photosynthesizing stems or phylloclades) which maintained relatively lower values 40-50 m² during the winter months of October to January, picked up during February and March and maintained higher values to the order of about 90-102 m² in April to August. *C. equisetifolia* therefore remained 'evergreen' although during the winter months majority of its leaves turned pale yellow (Fig. 4.1b, 4.9).

In *E. tereticornis* C-10 also peak values were obtained during April to November (Fig. 4.2b). These peak values were in the range of about 60 m² in 2008. The leaf area depicted a declining trend during the winter months with its values touching 25 m². Again during summer months of April to August leaf area values touched a maximum of 64 to 71 m² during April to August (Fig. 4.9).

Leaves of *T. arjuna* became very necrotic during the winter months of December, January and February though it maintained low leaf area values 13 to 21 m². *T. arjuna* depicted a sort of 'early summer deciduous' behavior, as the zero values of leaf area was attained only during the month of April for a brief period. Older leaves on the trees in March and April were highly senesced. Peak values of leaf area were quickly restored during the months of May and June to about 25 m² in both the years (Fig. 4.2a, 4.9).

M. azedarach presented a completely contrasting winter deciduous situation with its leaf area sharply declining to near zero in November and remaining so till early March (Fig. 4.4, 4.9). Bud burst and fresh leaf production started in March. It regained peak values of leaf area of about 34 to 42 m² during May to August in 2009 (Fig. 4.1a).

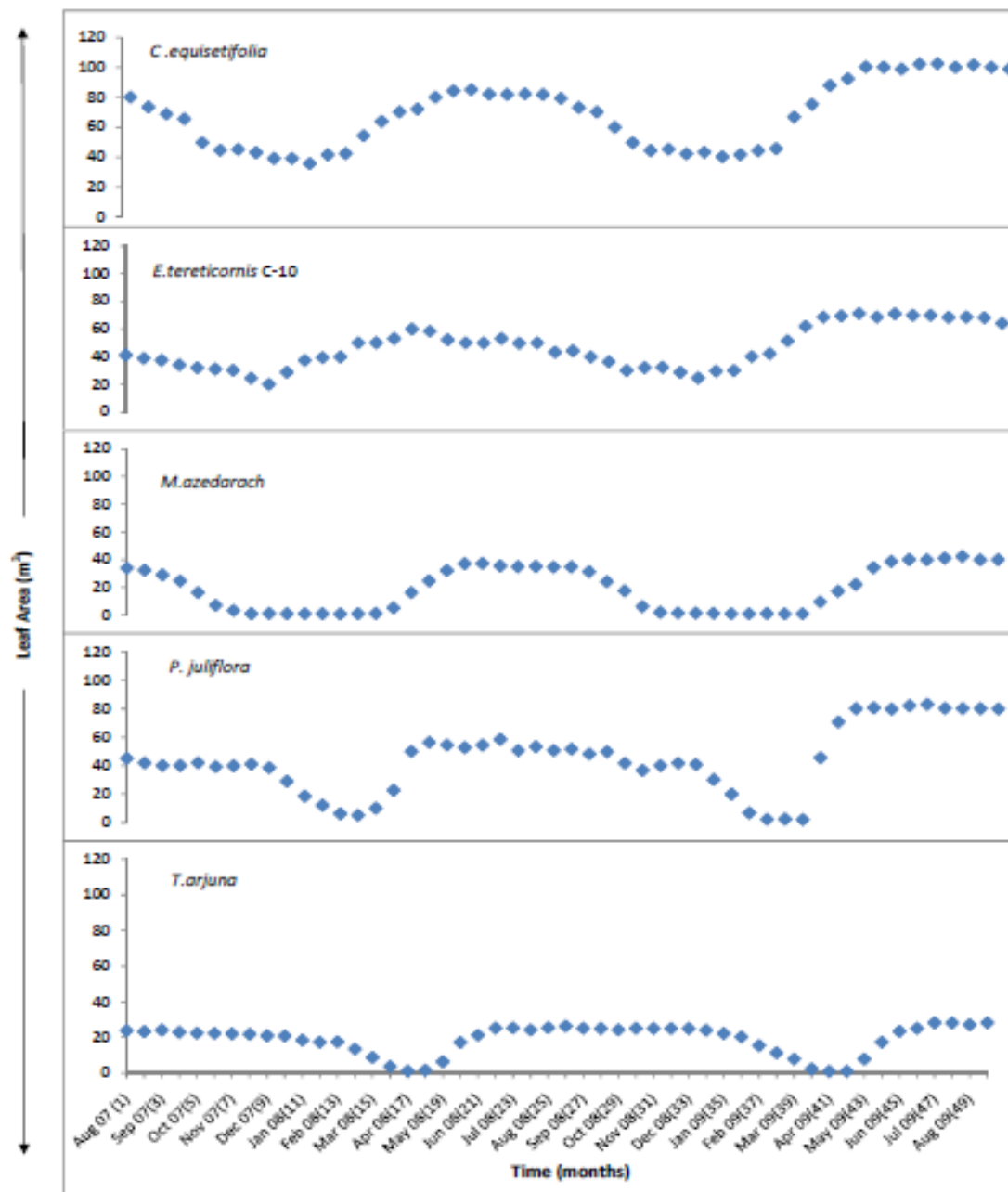


Fig. 4.9: Leaf area (m^2) of different lysimeter grown tree species from August 2007 through August 2009. (CD at 5% = 4.07)

P. juliflora also showed a rapid decline in the leaf area due to leaf shedding from November onwards and maintained a peak low during the months of February to the order of less than 10 m² in both the years (Fig. 4.4b, 4.9). Subsequent spring leaf regeneration was very brisk and leaf area of 45.6 m² was attained rapidly towards March 2009. Peak leaf area values of 83.2 were recorded in June 2009.

It may be added that leaves and tender stems of *P. juliflora* and *T. arjuna* are prone to frost in certain areas of north west India including Hisar. This damage could be avoided at the field site due to the microclimate moderating effect of wind break/screen of *Tamarix aphylla* raised around the lysimeter plot.

4.1.4 Annual growth cycle of tree species

To have simultaneous idea of the shoot growth through the annual cycle, suitable observations were made on the lysimeter grown tree species as explained in the section 3.5.3 (Materials and Methods). Results are presented in Fig.4.10a. It is seen that, in general all the tree species show an extension growth which continued throughout the year but for the winter months of end November to end February, when the growth was highly restricted or even absent. *T. arjuna* had halted extension activity even during April and early May. Results presented in Fig.15b show that number of leaves increased throughout the year in *C. equisetifolia* and *E. tereticornis* C-10 but for the winter months of end November to end March when it was very slow, maximum increment of leaf number was added by *C. equisetifolia* followed by *E. tereticornis* C-10, *P. juliflora*, *M. azedarach* and *T. arjuna*. *M. azedarach* was winter deciduous showing no leaves from November to March whereas *T. arjuna* was early summer deciduous showing no leaves in April to early May.

4.1.5 Meteorological parameters

It is imperative to have proper understanding of the day to day and seasonal fluctuations in individual climatic parameter, i.e. temperature, relative humidity, actual vapor pressure, vapor pressure deficit, wind speed, sunshine hours, radiation and pan evaporation (Ep) vis-à-vis the water biodrained (Wb). For this, a fortnightly mean of these parameter on the days of the Wb measurement experimentation i.e. 1st, 2nd, 3rd and 16th, 17th and 18th of the each month was considered. An outlined trend of these parameters is detailed below:

4.1.5a Temperature (T)

Figure 4.11 represents the maximum and minimum temperature and mean (mean of maximum and minimum) prevailing at the experimental site. It is obvious that the Hisar site has a highly seasonal climate with maximum temperatures touching 42°C in May 2008 and 43°C in May 2009. Likewise, the minimum temperature with -0.87°C (frost conditions) in January 2008 and 3°C in January

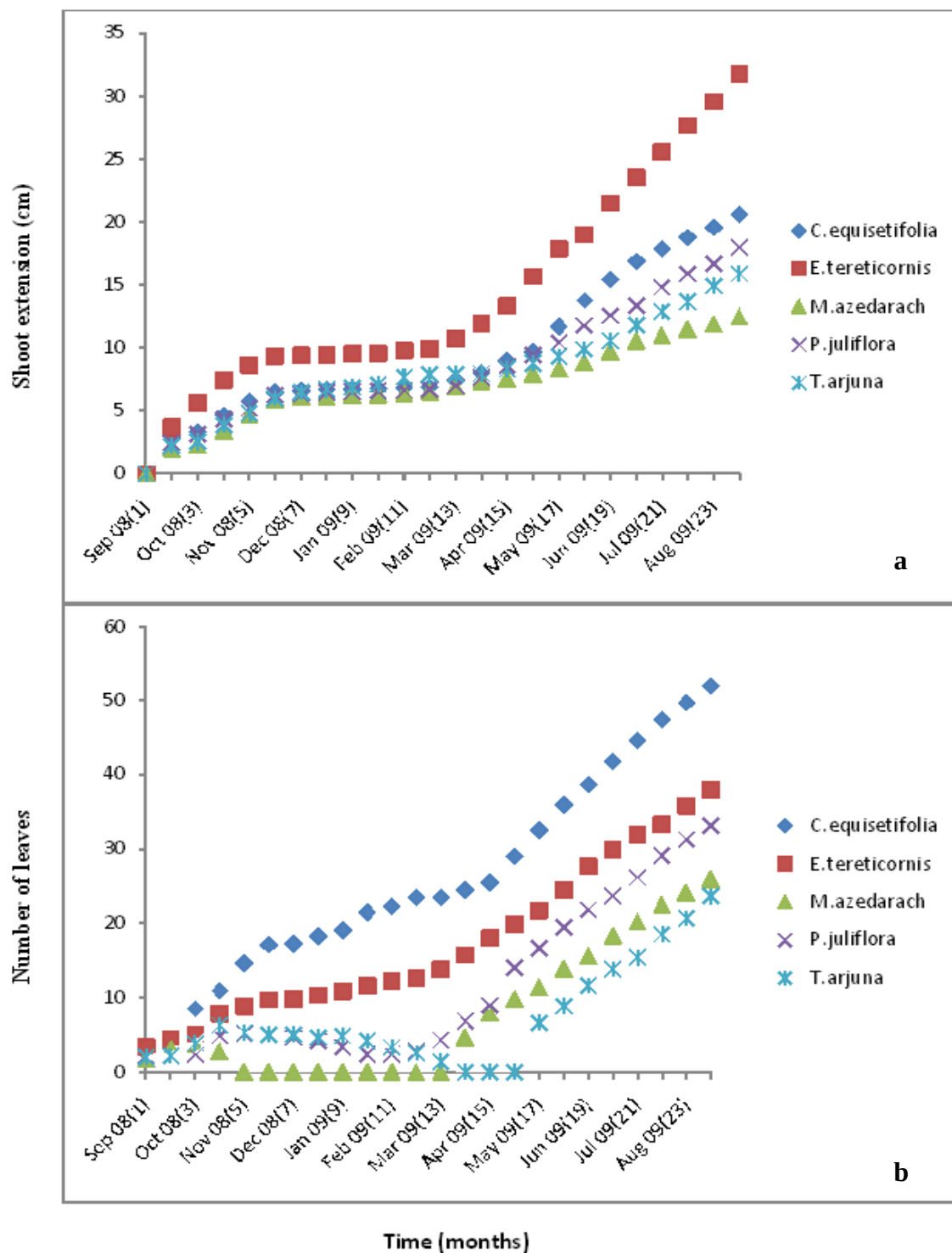


Fig.4.10: (a) Shoot extension and (b) number of leaves of different tree species grown in lysimeter from August 2007 to August 2009

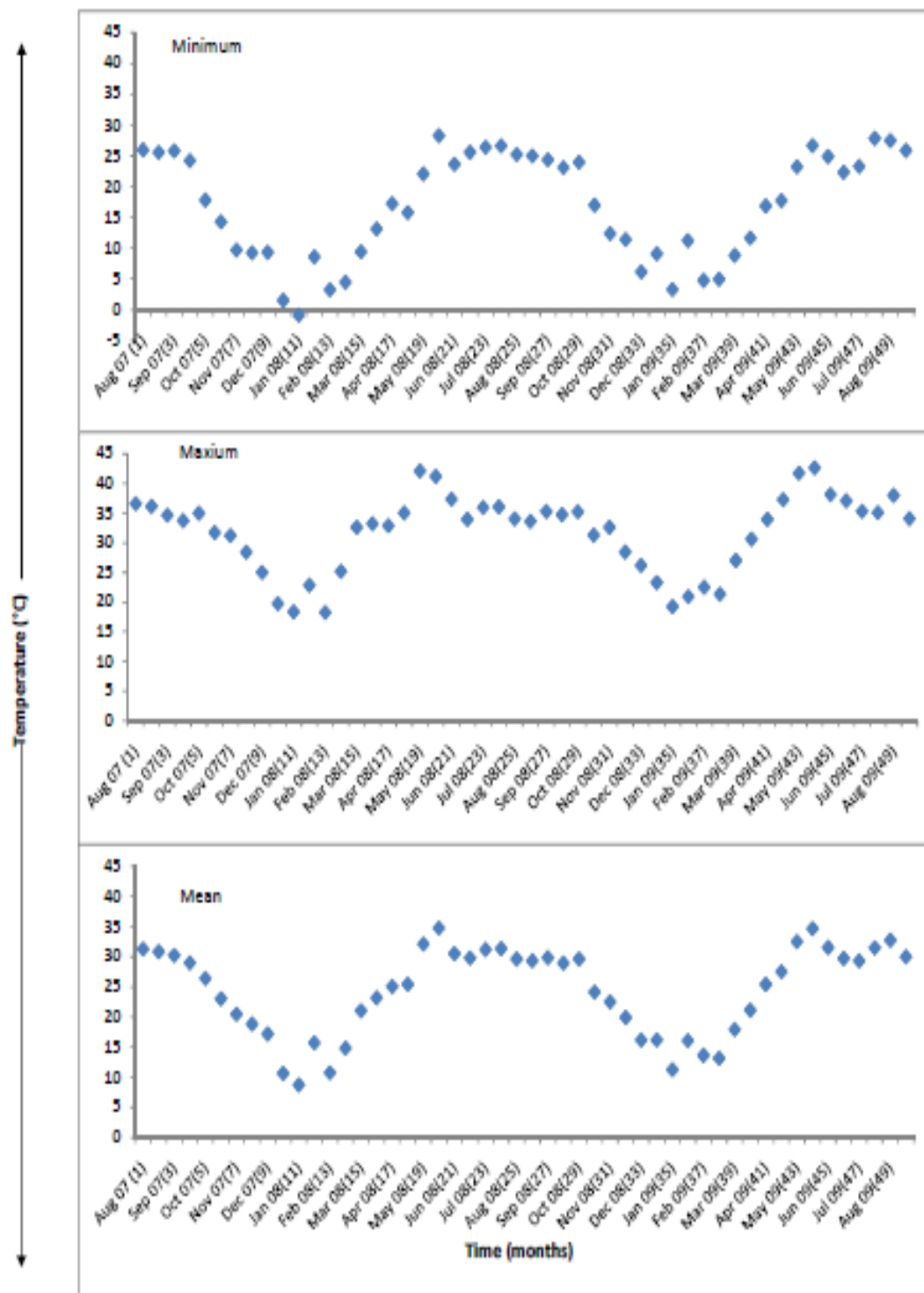


Fig. 4.11: Maximum, minimum and mean temperature ($^{\circ}\text{C}$) during the course of the experimental observation for two years starting August 2007.

2009. The mean temperature of particular days is also presented in Fig. 4.11. Such fluctuations have a maximum of about 35°C and minimum of about 9°C.

4.1.5b Actual vapor pressure (Avp)

No definitive trend could be observed between the morning and evening values of Avp (Fig. 4.12). Thus the actual vapor pressure in the morning could be slightly higher or lower than the evening Avp. The difference between the morning and evening Avp in either case was not very drastic. The mean of the morning and evening Avp accordingly followed the same trend.

It was interesting to note that on a seasonal scale high values of Avp were maintained during June to October e.g. the mean Avp values for a said period were in the range of 12.33 mm to 27.3 mm during the year 2008. On the other hand, distinctly low values of Avp were observed in November to May e.g. the range of mean Avp values during November 2008 to May 2009 was 6.37 to 16.10 mm.

4.1.5b Relative humidity (RH)

The RH in the morning, evening and mean of the two values is presented in Fig. 4.13. It is obvious that in general the RH was higher in the morning than in the evening. On the seasonal scale, RH values were higher in the monsoon seasons of July and August and continued to maintain relatively less values in the autumn months of October and November as well as in the winter months of December to March. Least values of RH were observed in months of end April to early June in both the years.

4.1.5c Vapor pressure deficit (VPD)

It is clear from results presented in Fig. 4.14 that VPD was consistently lower than 5% in the winter months of end November to late February. It recorded high values throughout the summer and early autumn months (end March to early November). The most interesting trend in the VPD fluctuation are the peak values in range of 23-27% during the dry summer month of May in both the years 2008 and 2009.

4.1.5d Wind speed (WS)

It becomes clear from the perusal of data presented in Fig. 4.15 that in general the wind speed maintained scatter between 1 to 4 km h⁻¹ during October to March. On the other hand, wind speed during April to August had a scatter in the range of 4 to 9.6 km h⁻¹. Therefore, it can be generalized that wind speed was higher during summer and ensuing monsoon period (April to August) as compared to the autumn and winter period (September to March).

4.1.5e Sunshine hours (SH)

Hisar lies at the latitude 29°10'N and longitude of 75°46'E. Consequently, there is a drastic seasonal variation of day length. The longest day of about 14 h is

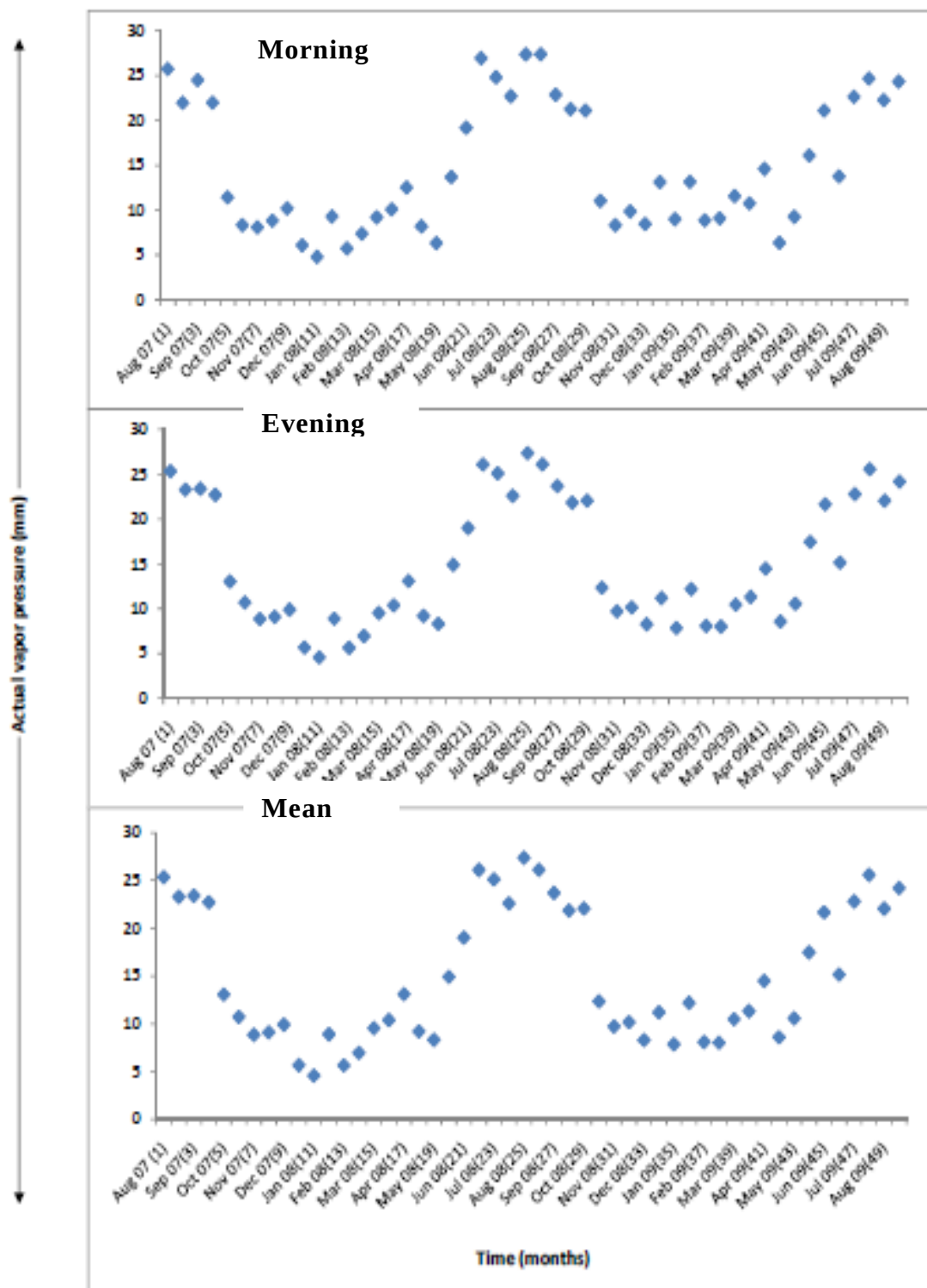


Fig. 4.12: Morning, evening and mean actual vapor pressure (mm of Hg) values obtained during the course of the experimental observations starting August 2007.

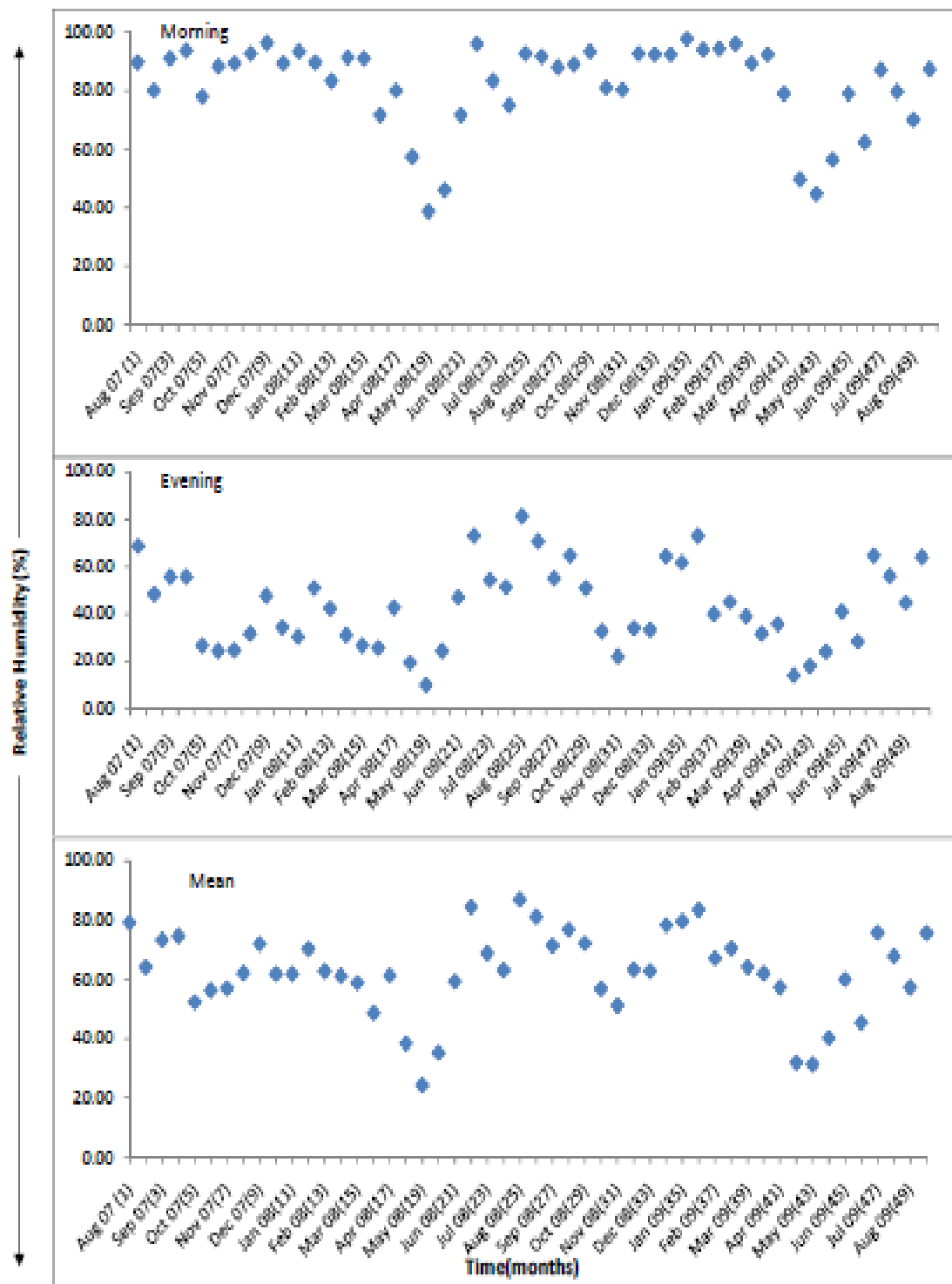


Fig. 4.13: Morning, evening and mean relative humidity (%) values obtained during the course of the experimental observations starting August 2007.

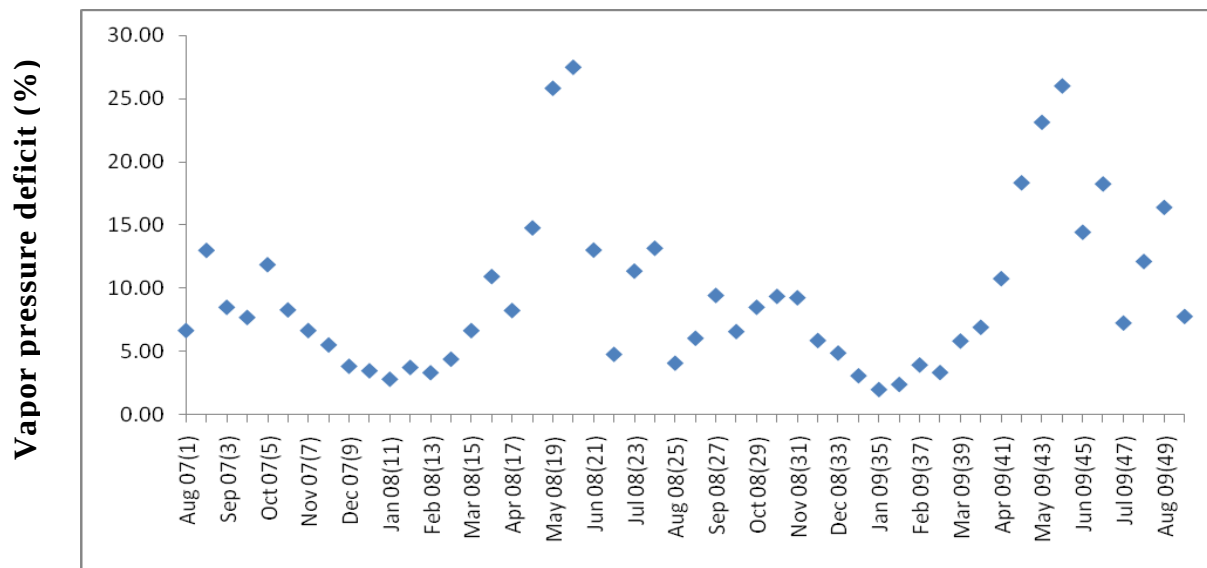


Fig. 4.14: Vapor pressure deficit (%) during the course of the experimental observation for two year starting August 2007.

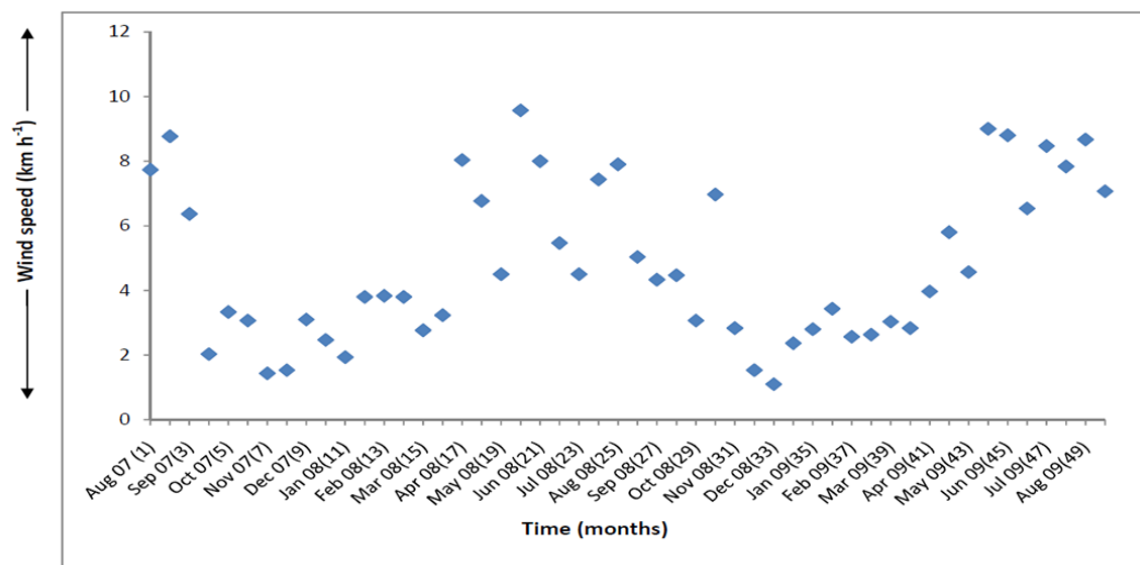


Fig. 4.15 Wind speed (km h^{-1}) prevailing during course of the experimental observations for two years starting August 2007

on 21st June and the shortest day of about 10.5 h is on 22nd December. However, as also seen from the sunshine hour data presented in Fig. 4.16, a considerable variation is found in the actual sunshine hours obtained, due to constant or intermittent cloudiness or fog. In general, sunshine hours were largest during the months of February to June and declined during the monsoon months of July to September. Barring exceptions the sunshine hours are at the lowest from November to January due to shorter day lengths, intermittent clouds and fog which engulfs this region in winter.

4.1.5f Radiation (Rad)

The insolation or incident radiation data at the latitude 30°N in Joules cm⁻² d⁻¹ showed that in general the radiation was highest in the months of May and June, when it was in the range of 3051 to 3089 J cm⁻² d⁻¹ (Fig. 4.17). It was lowest in the months of mid December to January (2332 to 2292 J cm⁻² d⁻¹). Within this range a sudden decline in the radiation during July to September is due to the wet season (kharif) was also seen.

4.1.5g Potential Evaporation (Ep)

The Ep values recorded during the time course of experimental observations are given in Fig. 4.18. It is seen that during the winter months of December to February, Ep maintained low level of 1 to 3 mm d⁻¹. The Ep values showed a sharp and steady increase thereafter reaching a peak in May to the order of 10.83 mm d⁻¹. During end June onwards lower values of Ep hovering around 5 mm d⁻¹ were met with Ep declined further in November reaching the values of about 2 mm d⁻¹ in December and onwards.

4.1.6 Water biodrained (Wb)

4.1.6a Observation frequency

As also indicated in the methodology part, (3.5.4) observations on Wb were recorded on three consecutive days fortnightly i.e. 1st, 2nd and 3rd and 16th, 17th and 18th of each month. Where rainfall coincided with the observation period, suitable correction was applied, adding the rainfall to the water table of each lysimeter. Such rainfall interference was very occasional and scanty. Therefore the fortnightly values of both climatic parameters as well as water biodrained reported in the subsequent sections of this experiment are means of the observations recorded on 1st, 2nd and 3rd and 16th, 17th and 18th of each month.

4.1.6b Wb in different tree species through the seasonal cycle

Results of Wb on fortnightly basis from August 2007 to August 2009 are presented in Fig. 4.19. Wb in *C. equisetifolia* which was to the order of about 10 L d⁻¹ during the winter months of December and February picked up during March and

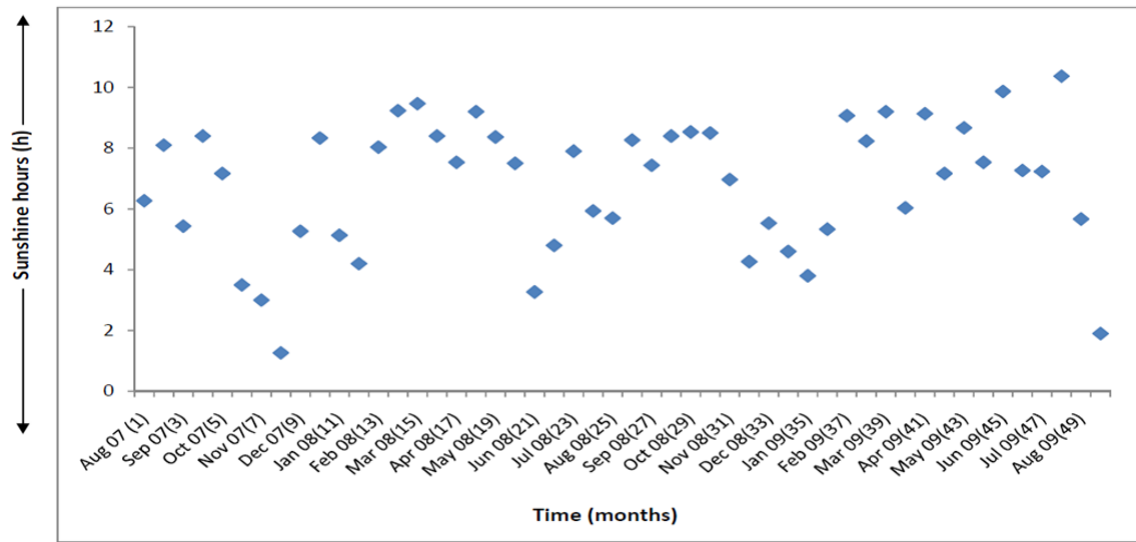


Fig. 4.16: Sunshine hours (h) obtained during the course of the experimental observations for two years starting August 2007.

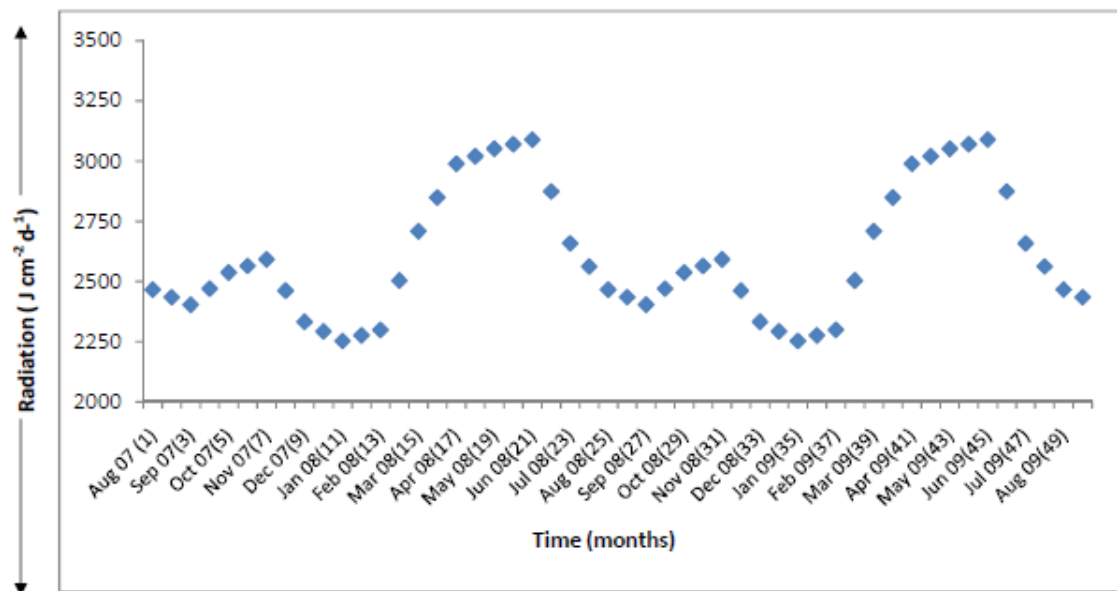


Fig. 4.17: Radiation ($\text{J cm}^{-2} \text{d}^{-1}$) obtained at Hisar. Experimental observations for two years starting August 2007.

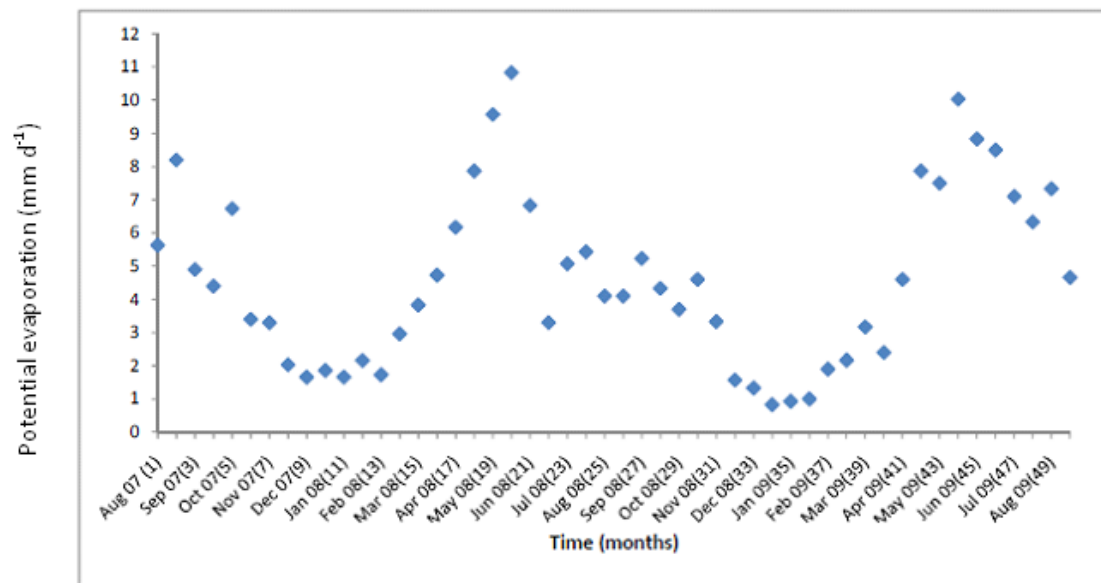


Fig. 4.18: Potential evaporation/PAN evaporation values (mm d^{-1}) obtained during the course of experimentation starting August 2007.

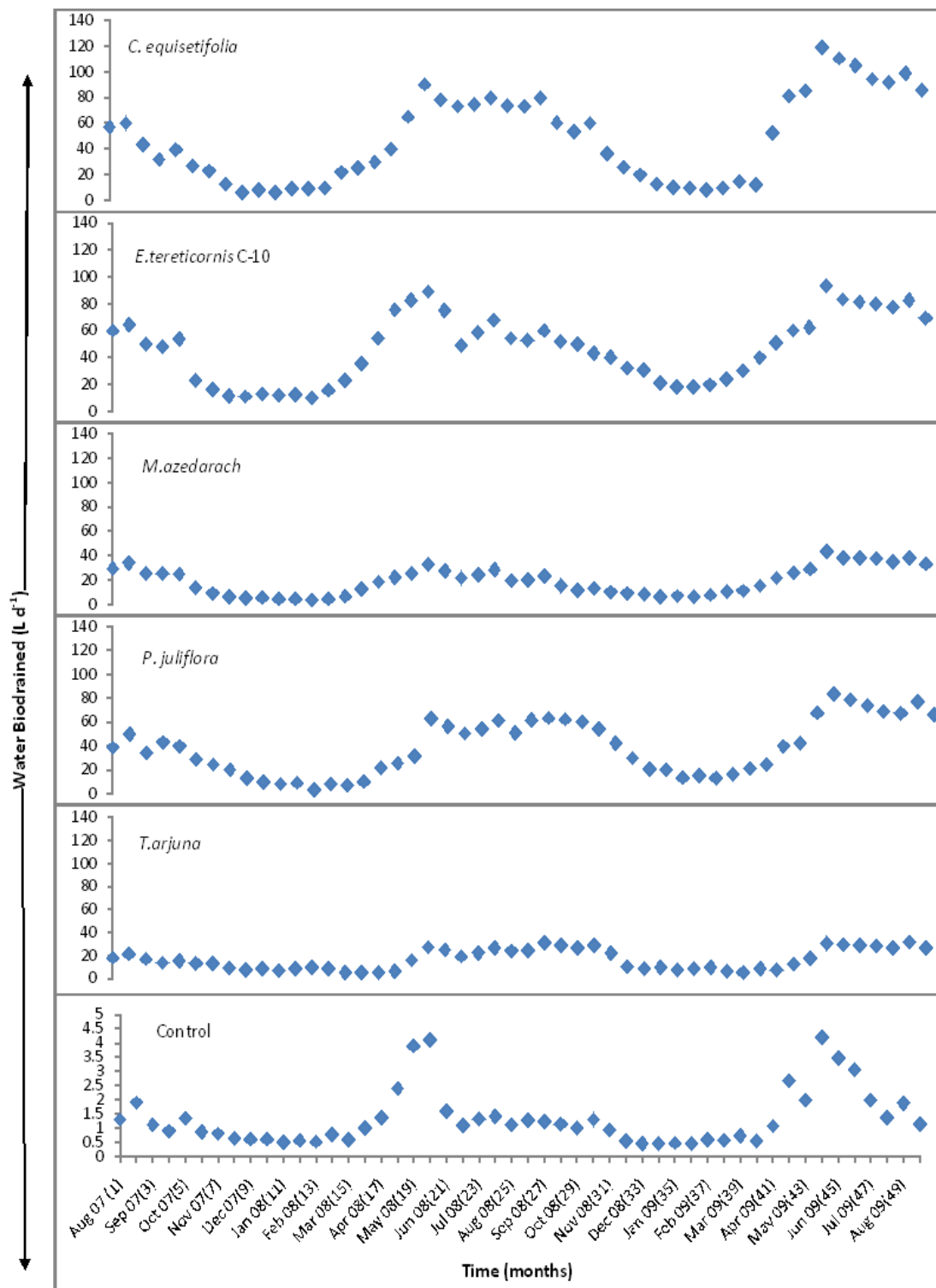


Fig. 4.19: Water biodrained (Wb) by different lysimeter-grown tree species as well as evaporation from the blank (control) lysimeters. (CD at 5% = 4.098)

April. Peak values of water biodrained to the tune of about 90 L d⁻¹ and 119 L d⁻¹ were recorded during May both in the year 2008 and 2009, respectively. During June, July and August water biodrained was slightly less as compared to May being in the range of 73 to 80 L d⁻¹ in 2008 and 86 to 110 L d⁻¹ in 2009. Gradual decline in the values of water biodrained were observed in the months of September, October and November touching the peak low values in winter towards December.

In *E. tereticornis* C-10 water biodrained was in the order of between 10 to 16 L d⁻¹ during the winter months of November and February and picked up during April to June. Peak values of water biodrained were recorded in the month of May which were 89 L d⁻¹ and 93 L d⁻¹ in 2008 and 2009, respectively. During June, July and August water biodrained was slightly less as compared to May being in the range of 49 to 74.8 L d⁻¹ in 2008 and 69.5 to 83.3 L d⁻¹ in 2009. Further, there was significant decline in the values of water biodrained during the months of September, October and November reaching the lowest values in winter towards December and January.

Wb in *M. azedarach* was in the range of only about 4 L d⁻¹ in the winter months of December and January. With the bud burst and leaf development Wb picked up during April to 22 L d⁻¹. Peak values were observed in May to the order of 32.5 and 43 L d⁻¹ in 2008 and 2009 respectively. During June, July and August water biodrained was slightly less as compared to May being in the range of 28 L d⁻¹ in 2008 and 38 L d⁻¹ in 2009. Gradual decline in the values of water biodrained were observed in the months of September, October and November again touching the trough in winter towards December and January.

In *P. juliflora* during the winter months of December and January, the water biodrained was to the order of about 8 L d⁻¹ in 2008 and about 15 L d⁻¹ in 2009. Water loss picked up rapidly during April and March and showed highest peak values of 63 L d⁻¹ and 84 L d⁻¹ in 2008 and 2009, respectively. Water loss declined slightly during June to August but overall biodrainage rates remained high till September. In October and November, a further decline occurred resulting in the lowest biodrainage values in December and onwards.

In *T. arjuna*, water biodrained again maintained lower rates during December to April which were in the range of 5 to 9 L d⁻¹ during 2008 and 5 to 12 L d⁻¹ in 2009. Water biodrained rates picked up sharply during May and maintained higher values in the range of 19 to 31 L d⁻¹ in 2008 and 17 to 31 L d⁻¹ in 2009. Interestingly, and in strong contrast to the other four species monitored, the peak values of water biodrained at the rate of 31 L d⁻¹ were depicted in September 2008 and 31.4 L d⁻¹ in 2009.

It was seen that significant amount of water was evaporated from the soil surface of the control lysimeters (Fig. 4.19). While during the months of winter i.e.

December to early February evaporation was less than 1 L d^{-1} , evaporation picked up very quickly during months of April reaching peak values of greater than 4 L d^{-1} in the month of May. However, during the moist summer months of June to August the evaporation rates declined to the range of $2\text{-}3 \text{ L d}^{-1}$. During September, October and November the evaporation values were still lower and, as already explained, lowest evaporation rates were again touched in December and January.

4.1.6c Cumulative Wb

Cumulative Wb values computed from Wb per year showed that they were in the order of 17 kL year^{-1} in *C. equisetifolia* and $16.8 \text{ kL year}^{-1}$ in *E. tereticornis* C-10 (Fig. 4.20a). These were followed by *P. juliflora* 14 kL year^{-1} , *M. azedarach* $6.80 \text{ kL year}^{-1}$ and *T. arjuna* 5.9 kL year^{-1} . The evaporation from the ground surface (control lysimeter) was only $0.48 \text{ kL year}^{-1}$. Thus as compared to the control, Wb was about 35 times in *C. equisetifolia* and *E. tereticornis* C-10.

4.1.6d Average Wb per day

Compared on per day basis the Wb followed the same trend i.e. *C. equisetifolia* (47 L d^{-1}) $\approx$ *E. tereticornis* C-10 (46 L d^{-1}) $>$ *P. juliflora* (38 L d^{-1}), *M. azedarach* (18 L d^{-1}) $>$ *T. arjuna* (16 L d^{-1}) $>$ control (1 L d^{-1}) (Fig. 4.20b).

4.1.6e Average seasonal fluctuation

Average seasonal fluctuation of water biodrained representing the average of Wb for all the five species for a period of two years (August 2007 to August 2009) is presented in Fig. 4.21. It is seen that such average reflects a clear trend of lowest values of Wb in winter (December - January) months followed by a rapid increase in the Wb during dry summer (April-May) and a declining trend in wet summer (July-August) which declined further during the autumn months (September-October). The highest values of Wb observed in end May i.e. 60.26 L d^{-1} and 72.46 L d^{-1} in 2008 and 2009, respectively, are noteworthy.

4.1.7 Correlation between different bidrainage traits

To understand the effect of different morphological characteristics of the tree species as well as different environmental parameters on Wb, it was considered imperative to work out the correlation coefficients amongst these. The correlation matrix of the five tree species for the characteristics of water biodrained (Ld^{-1}), height (cm), girth (cm), DBH (cm), leaf area (m^2), maximum temperature ($^{\circ}\text{C}$), minimum temperature ($^{\circ}\text{C}$), mean temperature ($^{\circ}\text{C}$), morning RH (%), evening RH (%), mean RH (%), VPD (%), wind speed (km h^{-1}), sunshine hours (h) and Ep (mm) are presented in Tables 4.1 to 4.5. In addition, for the sake of brevity and clarity, correlation coefficients of different parameters with Wb are summarized in Table 4.6.

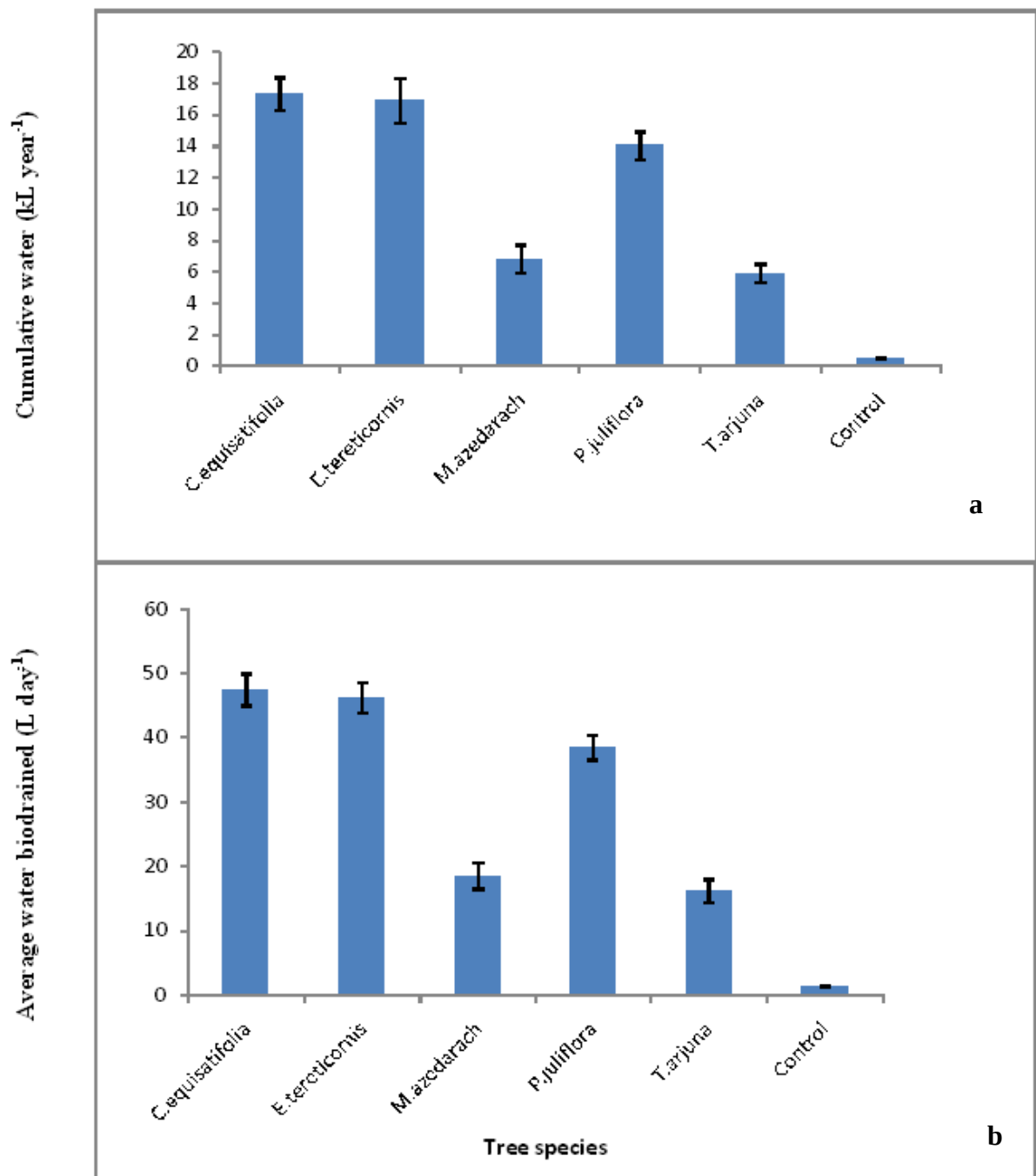


Fig. 4.20: (a) Cumulative water biodrained per year (kL year⁻¹) by different lysimeter grown tree species.
 (b) Water biodrained per day (L day⁻¹) by different lysimeter grown tree species.

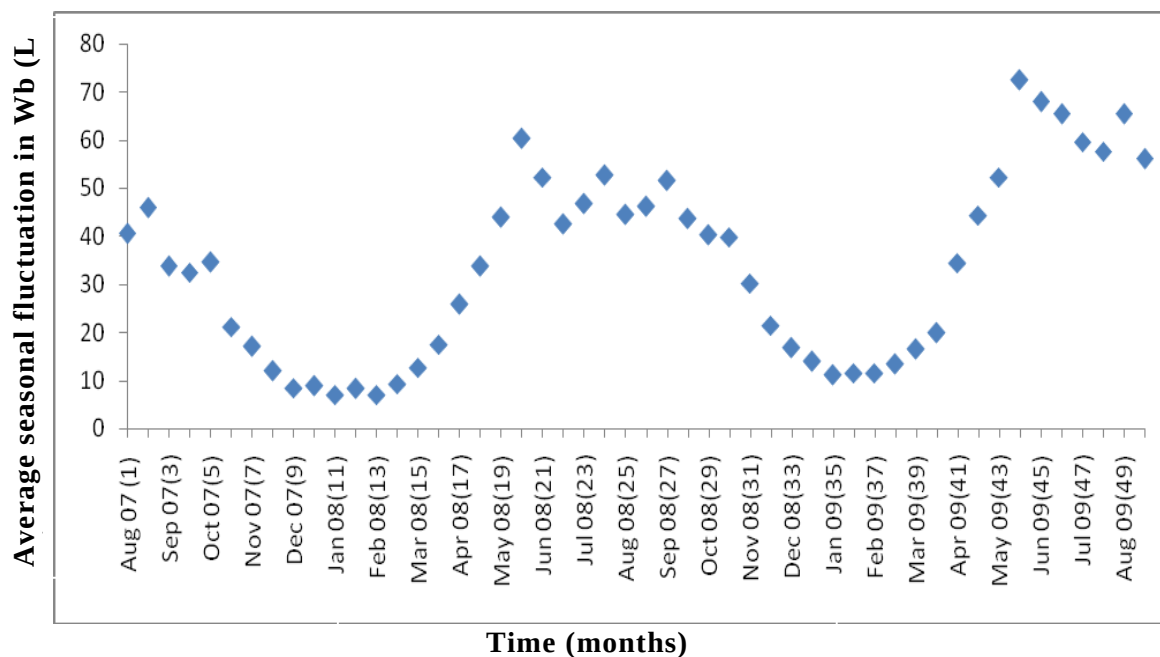


Fig. 4.21: Average seasonal fluctuation in water biodrained ($L d^{-1}$) values obtained during the course of the experimental observations starting August 2007.

4.1.7a Plant Height

It was detected (Table 4.1 and 4.6) that tree height, by and large had a weak positive correlation ($r = 0.232$ to 0.401^{**}) with water biodrained. Significant values of correlation coefficients were obtained only in *P. juliflora* ($r = 0.401^{**}$) and *C. equisetifolia* ($r = 0.366^{**}$). However, very high positive correlations are not reflected in this case.

4.1.7b Girth and DBH

Girth and DBH showed exactly the same correlation coefficient values as the two are related mathematically (Table 4.6). Here, an overall low but significant positive correlation ($r = 0.277$ to 0.396^{**}) was observed between girth/DBH and Wb.

4.1.7c Temperature (T)

One of the most interesting fact, which becomes obvious from the present correlation analysis is that in all the species, temperature, i.e. maximum ($r = 0.638^{**}$ to 0.885^{**}), minimum ($r = 0.793^{**}$ to 0.873^{**}) and mean ($r = 0.750^{**}$ to 0.902^{**}), had a highly significant positive correlation with water biodrained (Table 4.6). Most responsive species to the temperature variation was *E. tereticornis* C-10 with $r = 0.885^{**}$ (T max), $r = 0.867^{**}$ (T min) and $r = 0.902^{**}$ (T mean). On the other hand, least responsive to temperature was *T. arjuna* with $r = 0.638^{**}$ (T max), $r = 0.793^{**}$ (T min) and $r = 0.750^{**}$ (T mean) (Table 4.6).

Table 4.1: Correlation coefficients between different biodraniage parameters in *C. equisetifolia*

	Wb	Height	Girth	DBH	LA	T(max)	T(min)	T(mean)	Avp(mor)	Avp(eve)	Avp(mean)	RH(mor)	RH(eve)	RH(mean)	VPD	WS	SH	Rad	Ep
Wb	1																		
Height	0.366**	1																	
Girth	0.367**	0.966**	1																
DBH	0.367**	0.966**	1.000**	1															
LA	0.816**	0.436**	0.403**	0.403**	1														
T(max)	0.831**	0.087	0.059	0.06	0.753**	1													
T(min)	0.871**	0.096	0.061	0.061	0.726**	0.875**	1												
T(mean)	0.881**	0.095	0.062	0.062	0.761**	0.959**	0.977**	1											
Avp(mor)	0.735**	0.043	0.002	0.002	0.572**	0.653**	0.905**	0.822**	1										
Avp(eve)	0.623**	0.064	0.025	0.025	0.498**	0.487**	0.809**	0.692**	0.963**	1									
Avp(mean)	0.685**	0.054	0.014	0.014	0.540**	0.575**	0.865**	0.764**	0.991**	0.991**	1								
RH(mor)	-0.561**	-0.161	-0.186	-0.186	-0.569**	-0.656**	-0.405**	-0.529**	-0.014	0.152	0.07	1							
RH(eve)	0.087	0.045	0.022	0.022	0.006	-0.162	0.280*	0.093	0.573**	0.733**	0.659**	0.586**	1						
RH(mean)	-0.236	-0.055	-0.082	-0.082	-0.289*	-0.436**	-0.038	-0.216	0.341*	0.524**	0.436**	0.871**	0.909**	1					
VPD	0.704**	0.177	0.173	0.173	0.651**	0.805**	0.591**	0.705**	0.229	0.052	0.142	-0.934**	-0.510**	-0.791**	1.000				
WS	0.786**	0.134	0.146	0.146	0.713**	0.634**	0.740**	0.717**	0.627**	0.564**	0.601**	-0.471**	0.191	-0.127	0.550**	1			
SH	0.185	0.151	0.148	0.148	0.293*	0.213	0.132	0.172	0.077	0.022	0.05	-0.284*	-0.196	-0.265	0.281*	0.175	1		
Rad	0.531**	0.224	0.228	0.229	0.683**	0.702**	0.425**	0.562**	0.128	-0.008	0.061	-0.732**	-0.473**	-0.664**	0.743**	0.447**	0.303*	1	
Ep	0.809**	0.084	0.074	0.074	0.764**	0.865**	0.731**	0.814**	0.458**	0.290*	0.377**	-0.817**	-0.294*	-0.599**	0.900**	0.770**	0.351**	0.728**	1.000

*Significant at 5% and **Significant at 1%

Table 4.2: Correlation coefficients between different biodraniage parameters in *E. tereticornis* C-10

	Wb	Height	Girth	DBH	LA	T(max)	T(min)	T(mean)	Avp(mor)	Avp(eve)	Avp (mean)	RH(mor)	RH(eve)	RH(mean)	VPD	WS	SH	Rad	Ep
Wb	1																		
Height	0.269	1																	
Girth	0.339*	0.980**	1																
DBH	0.339*	0.980**	1.000**	1															
LA	0.624**	0.575**	0.616**	0.616**	1														
T(max)	0.885**	0.071	0.124	0.124	0.501**	1													
T(min)	0.867**	0.062	0.149	0.149	0.416**	0.875**	1												
T(mean)	0.902**	0.068	0.143	0.143	0.467**	0.959**	0.977**	1											
Avp(mor)	0.666**	0	0.099	0.099	0.256	0.653**	0.905**	0.822**	1										
Avp(eve)	0.543**	0.025	0.115	0.115	0.207	0.487**	0.809**	0.692**	0.963**	1									
Avp(mean)	0.610**	0.013	0.109	0.109	0.234	0.575**	0.865**	0.764**	0.991**	0.991**	1								
RH(mor)	-0.671**	-0.176	-0.179	-0.179	-0.529**	-0.656**	-0.405**	-0.529**	-0.014	0.152	0.07	1							
RH(eve)	-0.029	0.013	0.067	0.067	-0.141	-0.162	0.280*	0.093	0.573**	0.733**	0.659**	0.586**	1						
RH(mean)	-0.363**	-0.083	-0.052	-0.052	-0.358*	-0.436**	-0.038	-0.216	0.341*	0.524**	0.436**	0.871**	0.909**	1					
VPD	0.797**	0.180	0.199	0.199	0.534**	0.805**	0.591**	0.705**	0.229	0.052	0.142	-0.934**	-0.510**	-0.791**	1.000				
WS	0.802**	0.125	0.222	0.222	0.566**	0.634**	0.740**	0.717**	0.627**	0.564**	0.601**	-0.471**	0.191	-0.127	0.550**	1			
SH	0.264	0.157	0.176	0.176	0.373**	0.213	0.132	0.172	0.077	0.022	0.05	-0.284*	-0.196	-0.265	0.281*	0.175	1		
Rad	0.647**	0.237	0.212	0.212	0.684**	0.702**	0.425**	0.562**	0.128	-0.008	0.061	-0.732**	-0.473**	-0.664**	0.743**	0.447**	0.303*	1	
Ep	0.906**	0.082	0.149	0.149	0.607**	0.865**	0.731**	0.814**	0.458**	0.290*	0.377**	-0.817**	-0.294**	-0.599**	0.900**	0.770**	0.351*	0.728**	1.000

*Significant at 5% and **Significant at 1%

Table 4.3: Correlation coefficients between different biodraniage parameters in *M. azedarach*

	Wb	Height	Girth	DBH	LA	T(max)	T(min)	T(mean)	Avp(mor)	Avp(eve)	Avp(mean)	RH(mor)	RH(eve)	RH(mean)	VPD	WS	SH	Rad	Ep
Wb	1																		
Height	0.232	1																	
Girth	0.342*	0.953**	1																
DBH	0.343*	0.953**	1.000**	1															
LA	0.928**	0.184	0.269	0.27	1														
T(max)	0.822**	0.109	0.139	0.139	0.812**	1													
T(min)	0.858**	0.12	0.182	0.182	0.926**	0.875**	1												
T(mean)	0.869**	0.119	0.168	0.169	0.905**	0.959**	0.977**	1											
Avp(mor)	0.710**	0.074	0.155	0.155	0.833**	0.653**	0.905**	0.822**	1										
Avp(eve)	0.601**	0.084	0.157	0.158	0.754**	0.487**	0.809**	0.692**	0.963**	1									
Avp(mean)	0.662**	0.08	0.157	0.158	0.801**	0.575**	0.865**	0.764**	0.991**	0.991**	1								
RH(mor)	-0.562**	-0.143	-0.129	-0.129	-0.474**	-0.656**	-0.405**	-0.529**	-0.014	0.152	0.07	1							
RH(eve)	0.051	0.041	0.089	0.089	0.25	-0.162	0.280*	0.093	0.573**	0.733**	0.659**	0.586**	1						
RH(mean)	-0.258	-0.049	-0.013	-0.012	-0.092	-0.436**	-0.038	-0.216	0.341*	0.524**	0.436**	0.871**	0.909**	1					
VPD	0.719**	0.170	0.171	0.171	0.616**	0.805**	0.591**	0.705**	0.229	0.052	0.142	-0.934**	-0.510**	-0.791**	1.000				
WS	0.812**	0.114	0.214	0.214	0.803**	0.634**	0.740**	0.717**	0.627**	0.564**	0.601**	-0.471**	0.191	-0.127	0.550**	1			
SH	0.188	0.128	0.113	0.113	0.149	0.213	0.132	0.172	0.077	0.022	0.05	-0.284*	-0.196	-0.265	0.281*	0.175	1		
Rad	0.536**	0.206	0.137	0.137	0.461**	0.702**	0.425**	0.562**	0.128	-0.008	0.061	-0.732**	-0.473**	-0.664**	0.743**	0.447**	0.303*	1	
Ep	0.869**	0.072	0.136	0.136	0.784**	0.865**	0.731**	0.814**	0.458**	0.290*	0.377**	-0.817**	-0.294*	-0.599**	0.900**	0.770**	0.351**	0.728**	1.000

*Significant at 5% and **Significant at 1%

Table 4.4: Correlation coefficients between different bioclimate parameters in *P. juliflora*

	Wb	Height	Girth	DBH	LA	T(max)	T(min)	T(mean)	Avp(mor)	Avp(eve)	Avp(mean)	RH(mor)	RH(eve)	RH(mean)	VPD	WS	SH	Rad	Ep
Wb	1																		
Height	0.401**	1																	
Girth	0.396**	0.978**	1																
DBH	0.396**	0.978**	1.000**	1															
LA	0.823**	0.379**	0.388**	0.389**	1														
T(max)	0.784**	0.077	0.109	0.109	0.772**	1													
T(min)	0.873**	0.105	0.109	0.109	0.742**	0.875**	1												
T(mean)	0.861**	0.096	0.112	0.113	0.779**	0.959**	0.977**	1											
Avp(mor)	0.786**	0.068	0.041	0.041	0.589**	0.653**	0.905**	0.822**	1										
Avp(eve)	0.682**	0.096	0.06	0.06	0.461**	0.487**	0.809**	0.692**	0.963**	1									
Avp(mean)	0.741**	0.083	0.051	0.051	0.530**	0.575**	0.865**	0.764**	0.991**	0.991**	1								
RH(mor)	-0.406**	-0.135	-0.209	-0.209	-0.532**	-0.656**	-0.405**	-0.529**	-0.014	0.152	0.07	1							
RH(eve)	0.173	0.077	0.023	0.023	-0.033	-0.162	0.280*	0.093	0.573**	0.733**	0.659**	0.586**	1						
RH(mean)	-0.103	-0.022	-0.094	-0.094	-0.294*	-0.436**	-0.038	-0.216	0.341*	0.524**	0.436**	0.871**	0.909**	1					
VPD	0.719**	0.170	0.171	0.171	0.616**	0.805**	0.591**	0.705**	0.229	0.052	0.142	-0.934**	-0.510**	-0.791**	1.000				
WS	0.688**	0.153	0.192	0.192	0.614**	0.634**	0.740**	0.717**	0.627**	0.564**	0.601**	-0.471**	0.191	-0.127	0.550**	1			
SH	0.142	0.146	0.182	0.182	0.009	0.213	0.132	0.172	0.077	0.022	0.05	-0.284*	-0.196	-0.265	0.281*	0.175	1		
Rad	0.399**	0.18	0.268	0.268	0.546**	0.702**	0.425**	0.562**	0.128	-0.008	0.061	-0.732**	-0.473**	-0.664**	0.743**	0.447**	0.303*	1	
Ep	0.869**	0.072	0.136	0.136	0.784**	0.865**	0.731**	0.814**	0.458**	0.290*	0.377**	-0.817**	-0.294**	-0.599**	0.900**	0.770**	0.351*	0.728**	1.000

*Significant at 5% and **Significant at 1%

Table 4.5: Correlation coefficients between different biodraniage parameters in *T. arjuna*

	Wb	Height	Girth	DBH	LA	T(max)	T(min)	T(mean)	Avp(mor)	Avp(eve)	Avp(mean)	RH(mor)	RH(eve)	RH(mean)	VPD	WS	SH	Rad	Ep
Wb	1																		
Height	0.276	1																	
Girth	0.277	0.994**	1																
DBH	0.277	0.994**	1.000**	1															
LA	0.613**	0.008	0.002	0.002	1														
T(max)	0.638**	0.084	0.088	0.088	-0.009	1													
T(min)	0.793**	0.1	0.089	0.089	0.296*	0.875**	1												
T(mean)	0.750**	0.096	0.091	0.091	0.17	0.959**	0.977**	1											
Avp(mor)	0.775**	0.053	0.029	0.029	0.501**	0.653**	0.905**	0.822**	1										
Avp(eve)	0.688**	0.07	0.038	0.039	0.539**	0.487**	0.809**	0.692**	0.963**	1									
Avp(mean)	0.738**	0.062	0.034	0.034	0.525**	0.575**	0.865**	0.764**	0.991**	0.991**	1								
RH(mor)	-0.255	-0.145	-0.166	-0.165	0.392**	-0.656**	-0.405**	-0.529**	-0.014	0.152	0.07	1							
RH(eve)	0.276	0.04	0.007	0.008	0.553**	-0.162	0.280*	0.093	0.573**	0.733**	0.659**	0.586**	1						
RH(mean)	0.037	-0.051	-0.081	-0.08	0.538**	-0.436**	-0.038	-0.216	0.341*	0.524**	0.436**	0.871**	0.909**	1					
VPD	0.434**	0.172	0.184	0.184	-0.225	0.805**	0.591**	0.705**	0.229	0.052	0.142	-0.934**	-0.510**	-0.791**	1.000				
WS	0.645**	0.133	0.121	0.121	0.13	0.634**	0.740**	0.717**	0.627**	0.564**	0.601**	-0.471**	0.191	-0.127	0.550**	1			
SH	0.072	0.135	0.114	0.114	-0.344*	0.213	0.132	0.172	0.077	0.022	0.05	-0.284*	-0.196	-0.265	0.281*	0.175	1		
Rad	0.159	0.187	0.215	0.215	-0.529**	0.702**	0.425**	0.562**	0.128	-0.008	0.061	-0.732**	-0.473**	-0.664**	0.743**	0.447**	0.303*	1	
Ep	0.557**	0.084	0.085	0.085	-0.124	0.865**	0.731**	0.814**	0.458**	0.290*	0.377**	-0.817**	-0.294*	-0.599**	0.900**	0.770**	0.351*	0.728**	1.000

*Significant at 5% and **Significant at 1% .

Table 4.6: Summary table of correlation coefficients between different morphological and environmental parameters and water biodrained of different tree species

	W	Height	Girth	DBH	LA	T(max)	T(min)	T(mean)	Avp(mor)	Avp(eve)	Avp(mean)	RH(mor)	RH(eve)	RH(mean)	VPD	WS	SH	Rad	Ep
<i>C.equisetifolia</i>	1	0.366*	0.367*	0.367*	0.816*	0.831*	0.871*	0.881**	0.735**	0.623**	0.685**	51**	0.087	-0.236	0.704*	0.786*	0.18	0.531*	0.809*
<i>E. tereticornis C-10</i>	1	0.269	0.339*	0.339*	0.624*	0.885*	0.867*	0.902**	0.666**	0.543**	0.610**	71**	-0.029	-0.363**	0.797*	0.802*	0.26	0.647*	0.906*
<i>M.azedarach</i>	1	0.232	0.342*	0.343*	0.928*	0.822*	0.858*	0.869**	0.710**	0.601**	0.662**	52**	0.051	-0.258	0.719*	0.812*	0.18	0.536*	0.869*
<i>P.juliflora</i>	1	0.401*	0.396*	0.396*	0.823*	0.784*	0.873*	0.861**	0.786**	0.682**	0.741**	96**	0.173	-0.103	0.719*	0.688*	0.14	0.399*	0.869*
<i>T.arjuna</i>	1	0.276	0.277	0.277	0.613*	0.638*	0.793*	0.750**	0.775**	0.688**	0.738**	-0.255	0.276	0.037	0.434*	0.645*	0.07	0.159	0.557*
Mean	1	0.309	0.344	0.344	0.761	0.792	0.852	0.853	0.734	0.627	0.687	0.491	0.123	0.199	0.675	0.747	0.17	0.454	0.802

*Significant at 5% and **Significant at 1%

4.1.7d Actual vapor pressure (Avp)

Again it is of interest to note that Actual vapor presence (Avp) also had a significant positive correlation with Wb (Table 4.6). The correlation values were stronger for the morning Avp being in the range of 0.666** to 0.786** than for the 0.543** to 0.688** range for the evening Avp. The Avp mean had a range of $r = 0.610^{**}$ to 0.741^{**} .

4.1.7e Relative Humidity (RH)

Wb correlation with RH appeared to be important but a bit complex (Table 4.1-4.6). It should be noted that in general the RH was higher during the morning (7:30 a.m.) compared with the evening (2:30 p.m.) (Fig. 4.14). Accordingly, a negative correlation extending within a significant range ($r = -0.255$ to -0.671^{**}) existed between the Wb and RH morning in the five tree species (Table 4.6). However, the RH evening in general showed poor positive non-significant correlation ($r = -0.029$ to 0.276) with RH evening. The RH mean values accordingly showed lesser negative correlation values in non-significant to significant range ($r = 0.037$ to -0.363^{**}) with Wb in the tree species.

It would be of interest to note here that temperature (maximum, minimum and mean) had a positive correlation with Wb but correlation coefficients between RH (morning) and temperature ($r = -0.656^{**}$ T max, -0.405^{**} T min and -0.529^{**} T mean) were significantly negative (Table 4.1), and correlation coefficients between RH evening and temperature were neutral ($r = -0.162$, T max, 0.280^{*} T min and 0.093 T mean). Furthermore, the correlation between RH mean and temperature ($r = -0.436^{**}$, Tmax; -0.038 T min and -0.216 T mean) were also slightly negative (Table 4.1).

4.1.7f Vapor pressure deficit (VPD)

Results presented in Table 4.1 to 4.6 shows that vapor pressure deficit VPD in different tree species showed a significant positive correlation in the range of 0.434^{**} in *T. arjuna* to 0.792^{**} in *E. tereticornis* C-10. It is noteworthy that VPD showed a significant positive correlation with maximum temperature ($r = 0.805^{**}$), minimum temperature ($r = 0.591^{**}$) and mean temperature ($r = 0.705^{**}$). However, its correlation with relative humidity morning, evening and mean was significantly negative being -0.934^{**} , -0.510^{**} and -0.791^{**} , respectively.

4.1.7g Wind Speed (WS)

It is seen that a highly positive and significant correlation existed between the wind speed and Wb in different tree species ($r = 0.645^{**}$ to 0.812^{**}) (Table 4.6). It is

interesting to consider further that wind speed had significant correlation coefficient with maximum ($r = 0.634^{**}$), minimum ($r = 0.740^{**}$) and mean ($r = 0.717^{**}$) temperatures (Table 4.1).

4.1.7h Sunshine hours (SH)

Despite the fact that the day length at Hisar (Lat: 29°10'N, Long: 75°46' E) varies from a low of about 10:30 h on 22 December, to about 14:00 h on 23 June, the sunshine hours had a weak non-significant correlation with Wb ($r = 0.072$ to 0.264) in different tree species (Table 4.1 to 4.6).

4.1.7i Radiation (Rad)

In strong contrast to sunshine hours, radiation had a significant positive correlation with Wb in majority of the cases being in the range of 0.159 to 0.647^{**} (Table 4.1 to 4.6). However, radiation had a significant positive correlation with maximum temperature ($r = 0.702^{**}$), minimum temperature ($r = 0.425^{**}$) and mean temperature ($r = 0.562^{**}$) as well as with VPD ($r = 0.743^{**}$).

4.1.7j Potential evaporation (Ep)

Another cardinal trend which emerges from the correlation analysis is the significant positive correlation between Ep and Wb in the range of 0.557^{**} to 0.906^{**} (Table 4.6). Interestingly Ep also had a correlation of $r = 0.770^{**}$ with wind speed, $r = 0.865^{**}$ (maximum temperature), 0.731^{**} (minimum temperature) and 0.814^{**} (mean temperature) with temperature, $r = -0.817^{**}$ (RH morning), -0.294^{*} (RH evening) and -0.599^{**} (RH mean) and 0.351^{**} with sunshine hours (Table 4.1).

4.1.8 Regression analysis

Regression models were worked out between Wb and different tree growth and environmental factors. The results are presented in Table 4.7 with respect to the five tree species. For the sake of brevity and to avoid repetition the details along with the significance are enumerated in the next chapter (section 5.15).

4.1.9 Trade off with surrounding vegetation

In order to quantify the effect of various tree species on the trade off with vegetation underneath the lysimeter grown trees. Three months old vegetation was harvested as detailed in the section (3.6.8). Results presented in Table 4.8 showed that the biomass (dry mass) per unit area was maximum in the control to the extent of being almost double (40 g m^{-2}) as compared to the five tree species. This was followed by *M. azedarach* (26 g m^{-2}), *T. arjuna* (24 g m^{-2}), *P. juliflora* (12 g m^{-2}), *E. tereticornis* C-10 (9 g m^{-2}) and *C. equisetifolia* (9 g m^{-2}).

Table 4.7: Regression models with respect to water biodrained and different biotic and abiotic factors in five tree species.

Sr. No. and Species	Regression equations
1. <i>C. equisetifolia</i>	i) $Wb = -50.307 + 4.047^{**}(T \text{ mean})$ [$r^2 = 0.78$] ii) $Wb = -99.378 + 3.958^{**}(T \text{ mean}) + 2.180^{**}(\text{Girth})$ [$r^2 = 0.88$] iii) $Wb = -91.604 + 3.119^{**}(T \text{ mean}) + 1.997^{**}(\text{Girth}) + 3.508^{**}(\text{WS})$ [$r^2 = 0.91$]
2. <i>E. tereticornis</i> C-10	i) $Wb = 7.439 + 8.407^{**}(\text{Ep})$ [$r^2 = 0.82$] ii) $Wb = -3.712 + 7.311^{**}(\text{Ep}) + 1.083 (\text{Avp mean})$ [$r^2 = 0.90$] iii) $Wb = -22.453 + 7.143^{**}(\text{Ep}) + 1.098^{**}(\text{Avp mean}) + 0.031^{**}(\text{Height})$ [$r^2 = 0.95$]
3. <i>M. azedarach</i>	i) $Wb = 6.087 + 0.668^{**}(\text{LA})$ [$r^2 = 0.86$] ii) $Wb = 2.503 + 0.461^{**}(\text{LA}) + 1.616^{**}(\text{Ep})$ [$r^2 = 0.91$] iii) $Wb = -4.099 + 0.421^{**}(\text{LA}) + 1.728^{**}(\text{Ep}) + 1.077^{**}(\text{DBH})$ [$r^2 = 0.93$] iv) $Wb = 24.003 + 0.402^{**}(\text{LA}) + 1.731^{**}(\text{Ep}) + 3.808^{**}(\text{DBH}) - 0.222^{**}(\text{Height})$ [$r^2 = 0.94$]
4. <i>P. juliflora</i>	i) $Wb = -27.236 + 2.722^{**}(T \text{ mean})$ [$r^2 = 0.74$] ii) $Wb = -56.601 + 2.625^{**}(T \text{ mean}) + 0.113^{**}(\text{Height})$ [$r^2 = 0.84$] iii) $Wb = -25.008 + 2.948^{**}(T \text{ mean}) + 0.121^{**}(\text{Height}) - 0.016^{**}(\text{Rad})$ [$r^2 = 0.87$] iv) $Wb = -10.590 + 2.948^{**}(T \text{ mean}) + 0.097^{**}(\text{Height}) - 0.018^{**}(\text{Rad}) + 0.223^{**}(\text{LA})$ [$r^2 = 0.88$]
5. <i>T. arjuna</i>	i) $Wb = -5.633 + 0.899^{**}(T \text{ mean})$ [$r^2 = 0.56$] ii) $Wb = -13.069 + 0.797^{**}(T \text{ mean}) + 0.526^{**}(\text{LA})$ [$r^2 = 0.80$] iii) $Wb = -22.079 + 0.773^{**}(T \text{ mean}) + 0.529^{**}(\text{LA}) + 1.658^{**}(\text{DBH})$ [$r^2 = 0.85$] iv) $Wb = -20.793 + 0.476^{**}(T \text{ mean}) + 0.611^{**}(\text{LA}) + 1.642^{**}(\text{DBH}) + 0.964^{**}(\text{Ep})$ [$r^2 = 0.87$]

Table 4.8: Ground vegetation biomass (g m^{-2}) produced beneath different lysimeter grown trees. (C.D. at 5% = 1.67).

Sr. No	Species	Biomass (g m^{-2})
1	<i>C.equisetifolia</i>	9.25
2	<i>E.tereticornis</i> C-10	9.21
3	<i>M.azedarach</i>	26.15
4	<i>P.juliflora</i>	12.27
5	<i>T.arjuna</i>	24.11
6	Control	40.17

4.2 EXPERIMENT 2

To study different physiological traits of tree species grown in lysimeters

As also explained in the Materials and Methods section (3.6), observations on different physiological parameters were recorded four times for the period of one year. This was done to cover the major seasons existing at Hisar i.e. April 08 (dry summer), July 08 (wet summer), October 08 (autumn) and January 09 (winter).

At the onset it may be added that due to winter deciduous nature of *M. azedarach*, no readings with respect to some parameters were made in January, 2009. Similarly, due to summer deciduous nature of *T. arjuna*, highly senescent leaves were present on the tree in the month of April and the values recorded were abnormal and ignored for the purpose of any conclusions.

4.2.1 Transpiration Rates (E)

Results presented in Fig. 4.22 indicated that in general, transpiration rates were higher in *C. equisetifolia* and *E. tereticornis* C-10 followed by *P. juliflora*. These were on the lowest side in *T. arjuna* and *M. azedarach*. For example, in the month of July 2008, transpiration was $6.46 \text{ mmol m}^{-2} \text{ s}^{-1}$ in *C. equisetifolia*, $6.28 \text{ mmol m}^{-2} \text{ s}^{-1}$ in *E. tereticornis* C-10, $5.81 \text{ mmol m}^{-2} \text{ s}^{-1}$ in *P. juliflora*, $4.33 \text{ mmol m}^{-2} \text{ s}^{-1}$ in *T. arjuna* and $3.45 \text{ mmol m}^{-2} \text{ s}^{-1}$ in *M. azedarach*. On a seasonal scale, in general, transpiration was highest in the month of July followed by April, October and least in the month of January.

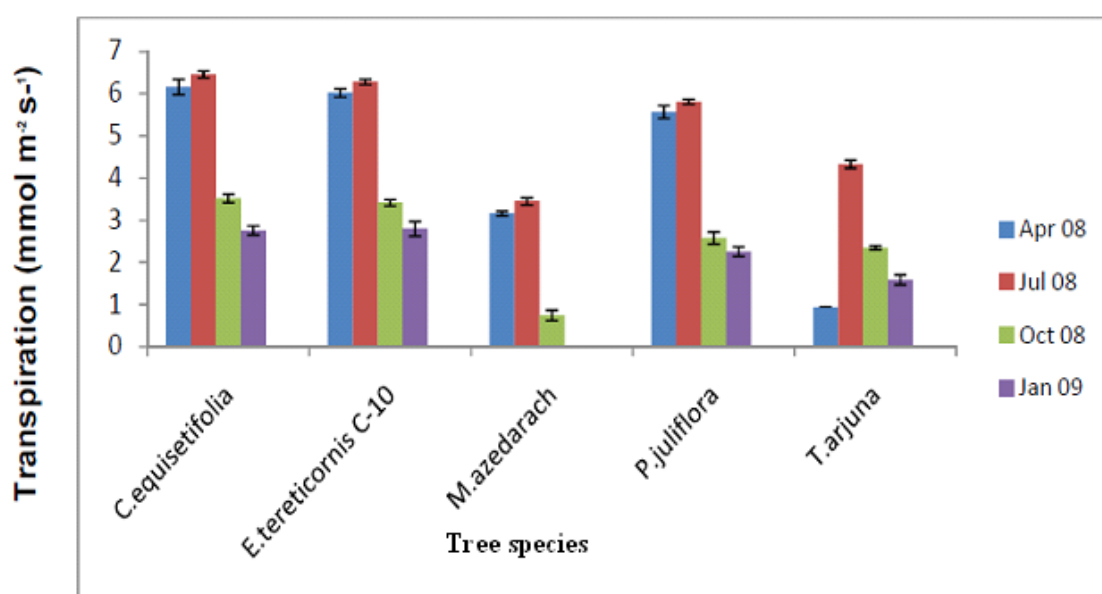


Fig. 4.22: Transpiration ($\text{mmol m}^{-2} \text{ s}^{-1}$) in different lysimeter-grown tree species at different times of year. Vertical bars indicate standard error.

4.2.2 Stomatal conductance (g_s)

C. equisetifolia followed by *E. tereticornis* C-10 and *P. juliflora* showed higher values of stomatal conductance. This was followed by *T. arjuna* and *M. azedarach* in decreasing order (Fig. 4.23). On a seasonal scale, highest values of g_s were found in the month of July followed by April, October and January in the decreasing order. Thus, *C. equisetifolia* recorded g_s of $6.46 \text{ mol m}^{-2} \text{ s}^{-1}$ in July, $6.16 \text{ mol m}^{-2} \text{ s}^{-1}$ in April, $3.52 \text{ mol m}^{-2} \text{ s}^{-1}$ in October and $2.76 \text{ mol m}^{-2} \text{ s}^{-1}$ in January.

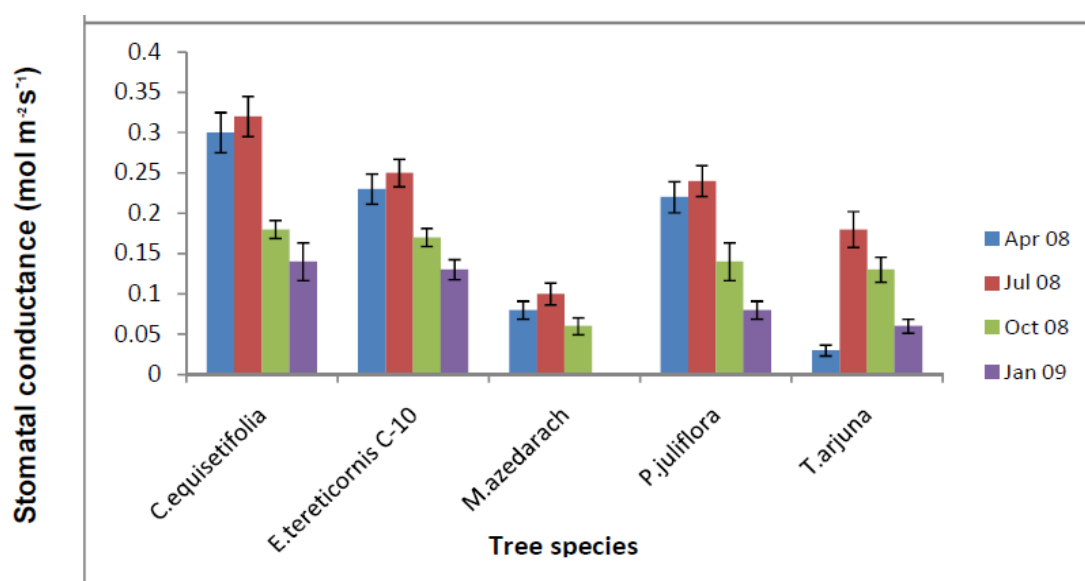


Fig. 4.23: Stomatal conductance in different lysimeter-grown tree species at different times of year. Vertical bars indicate standard error.

4.2.3 Relative water content (RWC)

Fig. 4.24 shows that in general RWC of *C. equisetifolia*, *E. tereticornis* C-10, *P. juliflora* was at par with each other while both *M. azedarach* and *T. arjuna* maintained slightly lower levels of RWC. It was highest in the month of July closely followed by April where as relatively lower values of RWC were recorded in the months of October and January. For example, RWC of *E. tereticornis* C-10 was 82.26% in April 2008, 85.21% in July 2008, 79.52% in October 2008 and 76.54% in January 2009.

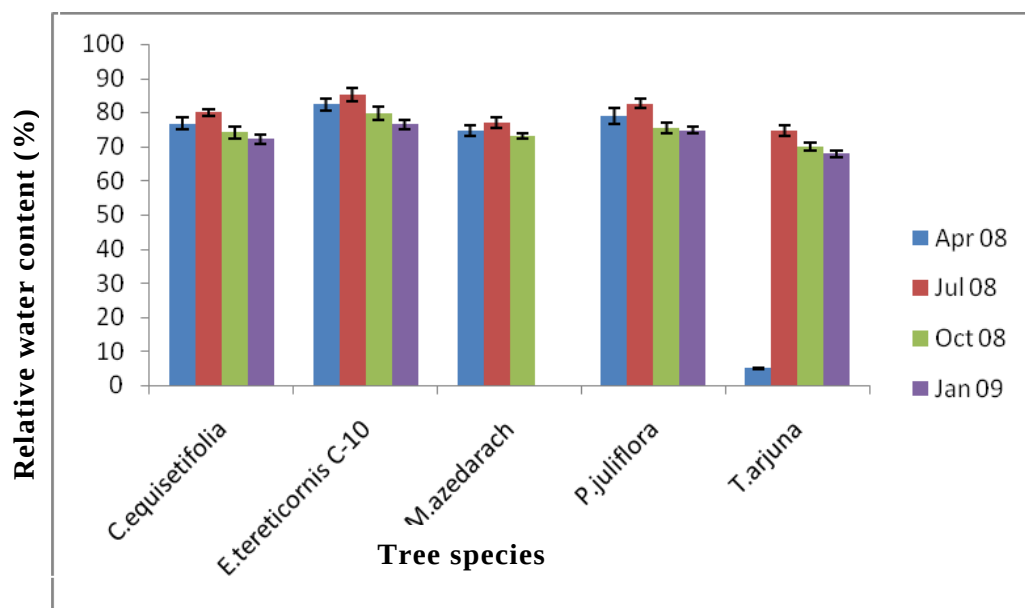


Fig. 4.24: Relative water content (RWC) (%) in tree species grown in lysimeter at different intervals of year. Vertical bars indicate standard error.

4.2.4 Leaf water retention (LWR)

Data illustrated in Fig. 4.25 shows that over all LWR was highest in *E. tereticornis* C-10 followed by *T. arjuna* and *C. equisetifolia*. This was further followed by *P. juliflora* and *M. azedarach* in the decreasing order. For example LWR (%) in July was 47.55 % in *E. tereticornis* C-10, 41.83 % in *T. arjuna*, 39.76 % in *C. equisetifolia*, 37.56 % in *P. juliflora* and 28.66 % in *M. azedarach*. On a seasonal scale LWR (%) followed the trend July>April>October>January.

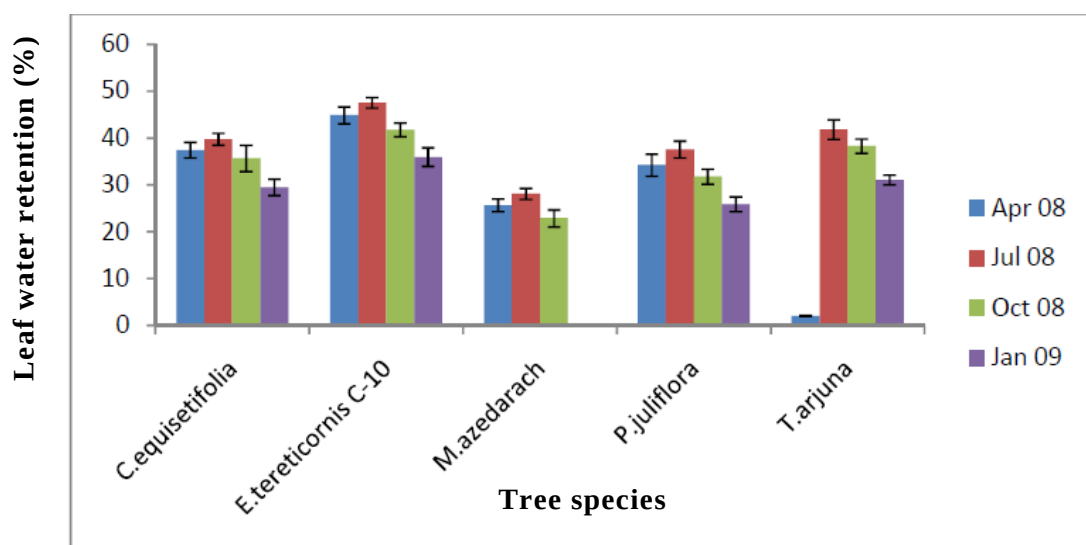


Fig. 4.25: Leaf water retention (LWR) (%) in lysimeter-grown tree species at different times of year. Vertical bars indicate standard error.

4.2.5 Potometric water Loss (PWL)

Results presented in Fig. 4.26 show that PWL ($\text{ml H}_2\text{O}/\text{cm}^2$ leaf area/day) was maximum in *E. tereticornis* C-10 and *C. equisetifolia*, followed in decreasing order by *P. juliflora*, *M. azedarach* and *T. arjuna*. On a seasonal scale PWL was maximum in month of July followed by the month of April, October and January in declining order. Thus for example in July PWL was 0.292 in *E. tereticornis* C-10, 0.285 in *C. equisetifolia*, 0.248 in *P. juliflora*, 0.197 in *M. azedarach* and 0.168 in *T. arjuna*.

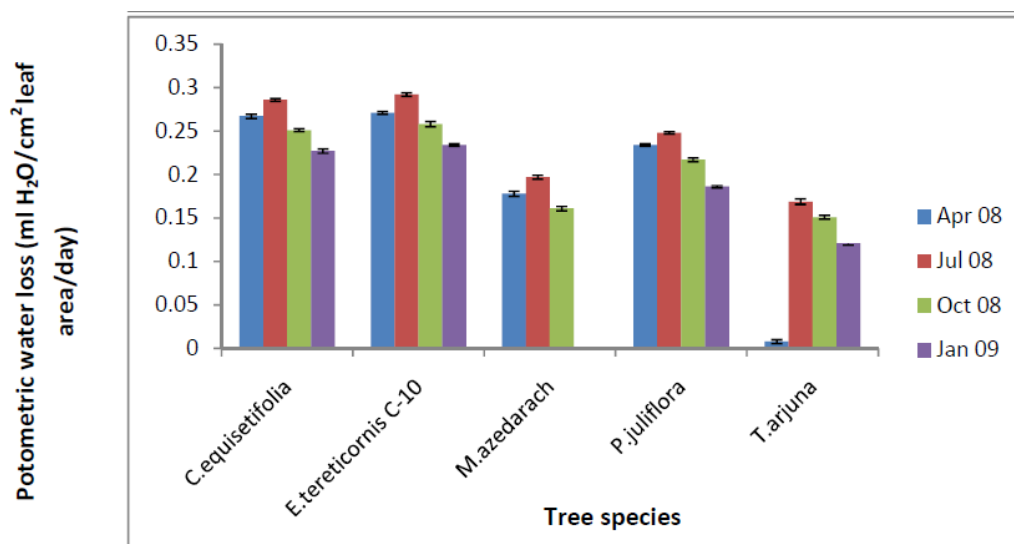
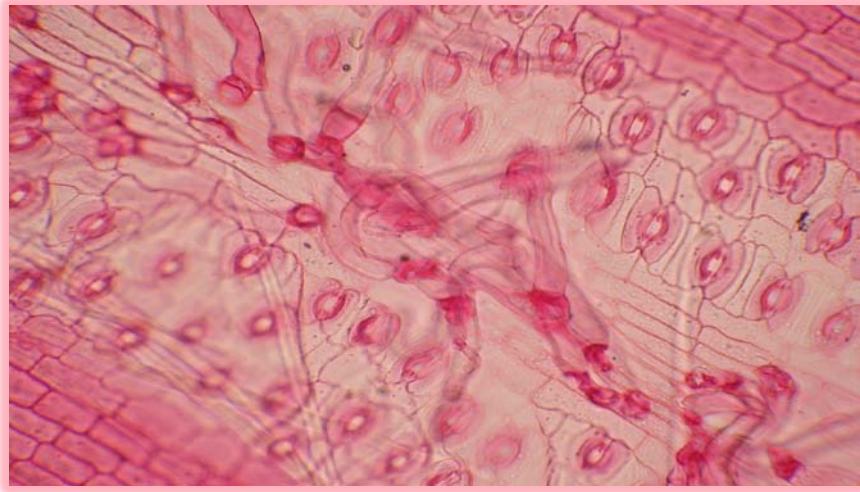


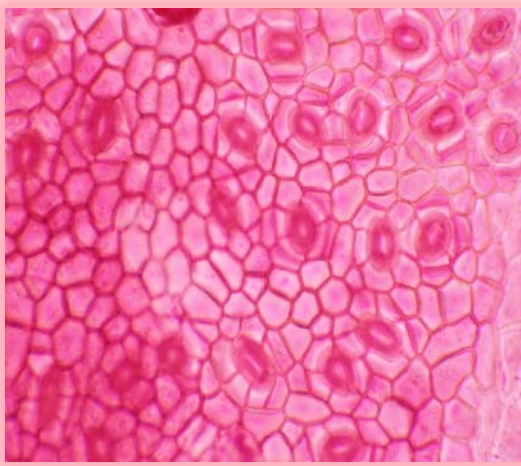
Fig. 4.26: Potometric water loss (PWL) ($\text{ml H}_2\text{O}/\text{cm}^2$ leaf area/day) at different intervals of year in tree species. Vertical bars indicate standard error.

4.2.6 Stomatal density

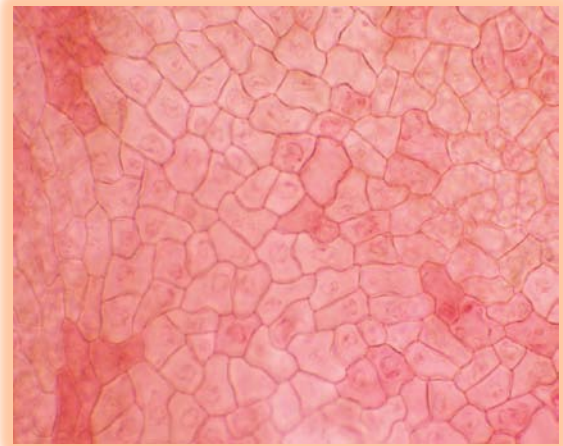
Results presented in Fig. 4.27 show that maximum total stomatal density (stomata mm^{-2} leaf area) of 670 mm^{-2} was in the phylloclade of *C. equisetifolia*. This was followed by nearly at par values of 416 in *M. azedarach*, 392 in *P. juliflora*, 387 in *E. tereticornis* C-10 and 377 in *T. arjuna* (Plate 4.1 and 4.2).



a



b



c

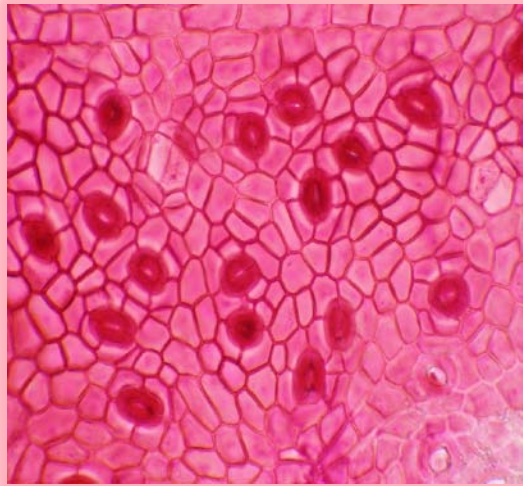


d

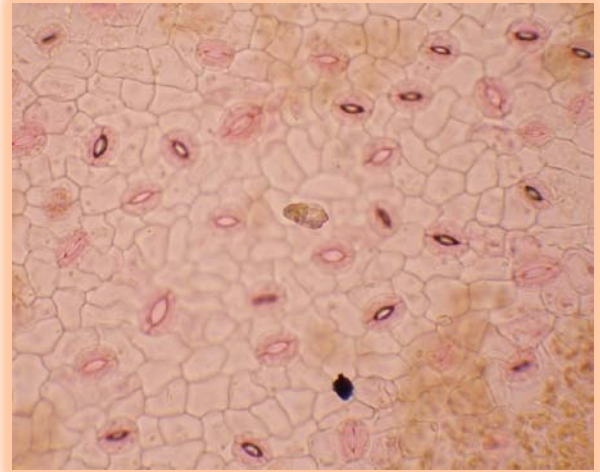


e

Plate 4.1: Stomatal density in (a) phylloclade of *C. equisetifolia* and on adaxial surface of (b) *E. tereticornis* C-10 (c) *M. azedarach* (d) *P. juliflora* and (e) *T. arjuna*



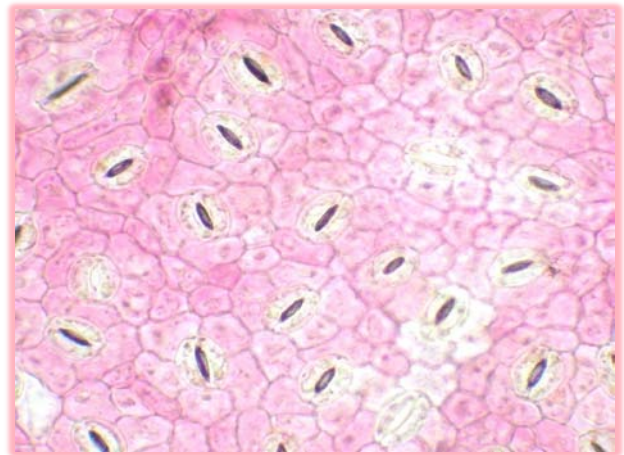
a



b



c



d

Plate 4.2: Stomatal density on abaxial surface of

(a) *E.tereticornis* C-10 (b) *M. azedarach* (c) *P. juliflora* and (d) *T.arjuna*

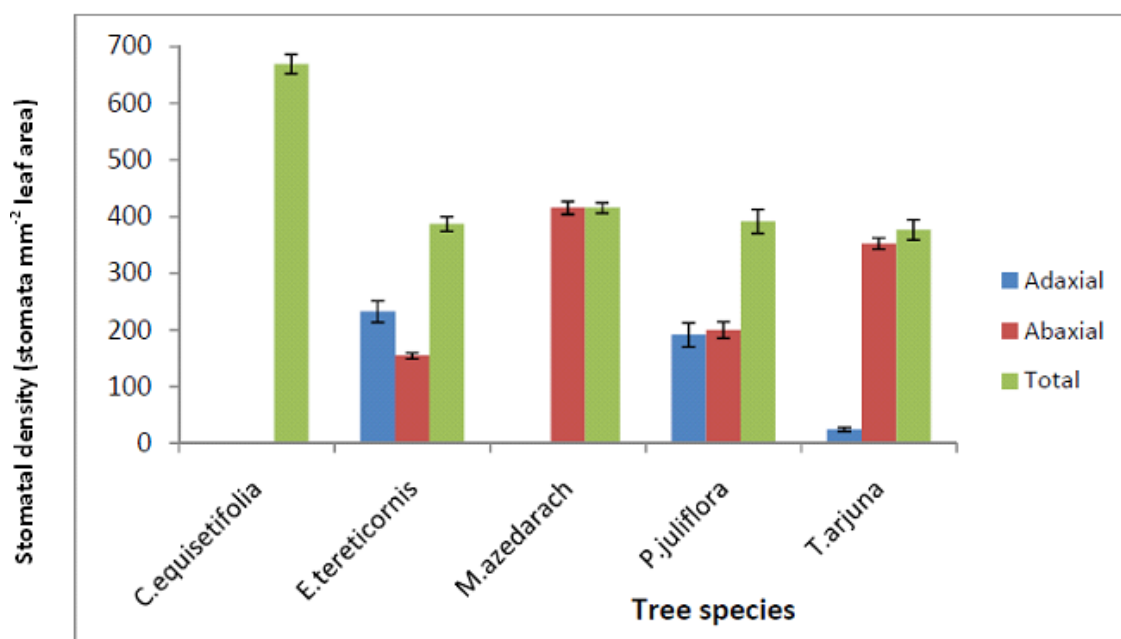


Fig. 4.27: Stomatal density (stomata mm⁻² leaf area) on adaxial surface and abaxial surface and total in different tree species. Vertical bars indicate standard error.

It was interesting to note that *M. azedarach* had no stomata on the adaxial surface. In *E. tereticornis* C-10 while number of stomata on the adaxial surface was greater than the abaxial surface, in *P. juliflora* the number of stomata on the adaxial and abaxial surface was nearly equal. In *T. arjuna*, however, only traces of stomata were present on the adaxial surface (24.5) as compared to the abaxial surface (352.5).

4.2.7 Width of tracheids and vessel elements

It is seen in Fig. 4.28 that in different tree species the width of tracheids was very narrow (8.75 μ m to 12.51 μ m) as compared to the vessels (88.38 μ m to 133.88 μ m). The widest tracheids were found in *T. arjuna* (12.51 μ m) where as the maximum vessel element width in the nearly equal range of 130 to 134 μ m was found in *E. tereticornis* C-10, *M. azedarach* and *P. juliflora* (Plate 4.3 and 4.4).

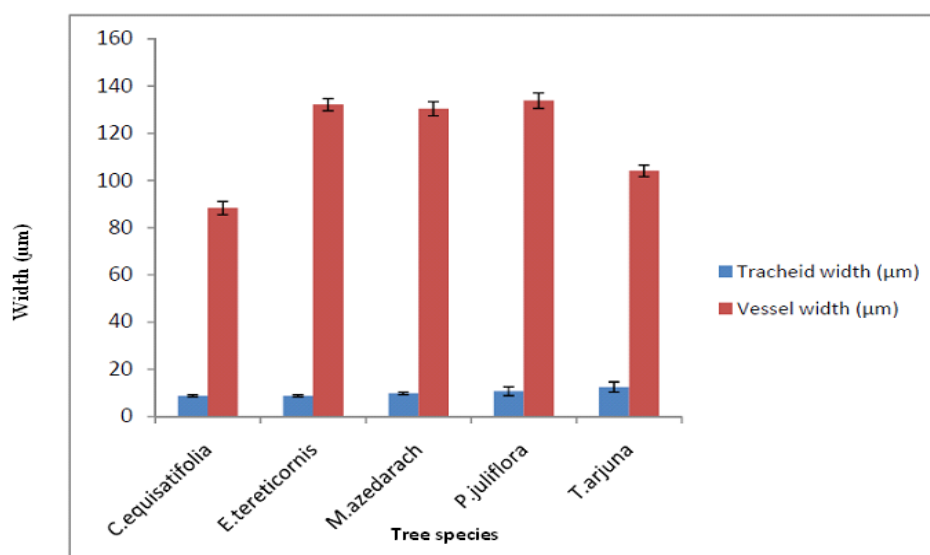


Fig. 4.28: Width of tracheids and vessels (µm) of different tree species. Vertical bars indicate standard error.

4.2.8 Length of tracheids and vessels elements

It was observed that the length of tracheids was maximum in *E. tereticornis* C-10 (548.6 µm) followed by *C. equisetifolia* (489.1 µm), *T. arjuna* (375.4 µm), *M. azedarach* (367.5) and *P. juliflora* (327.5 µm) in decreasing order (Fig. 4.29). Longest vessels were found in *T. arjuna* (612.5 µm) followed in decreasing order by *M. azedarach* (533.8 µm), *E. tereticornis* C-10 (509.3 µm), *P. juliflora* (428.8 µm) and *C. equisetifolia* (355.3 µm). It is interesting to note that vessel element length in *M. azedarach*, *P. juliflora* and *T. arjuna* was greater than that of tracheids (Plate 4.3 and 4.4).

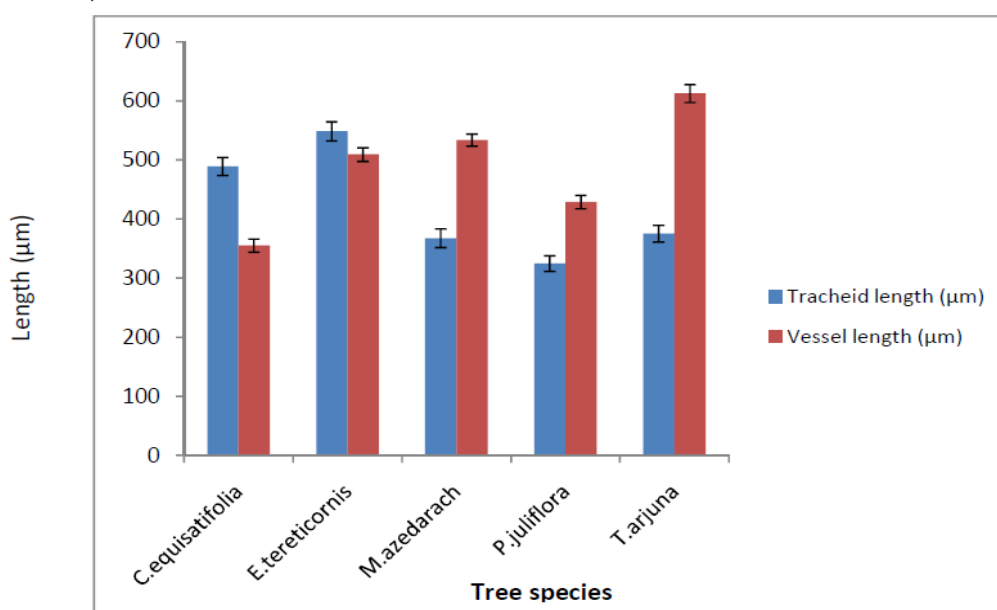
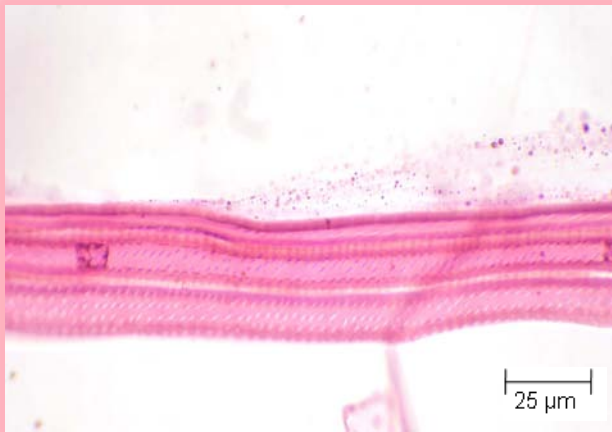


Fig. 4.29: Length of tracheids and vessels (µm) in lysimeter-grown tree species. Vertical bars indicate standard error.



a



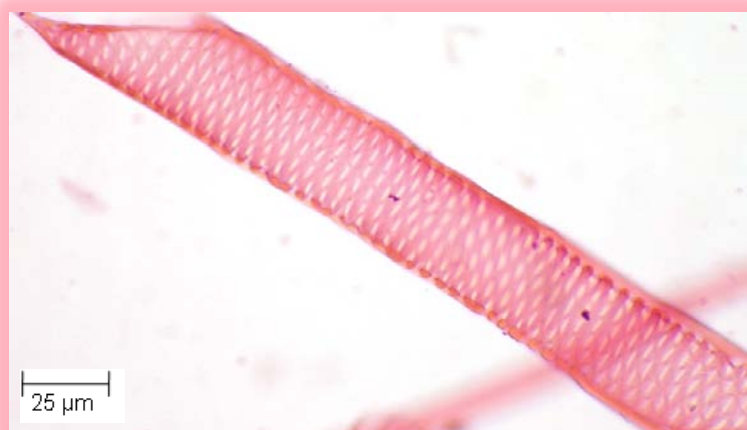
b



c



d



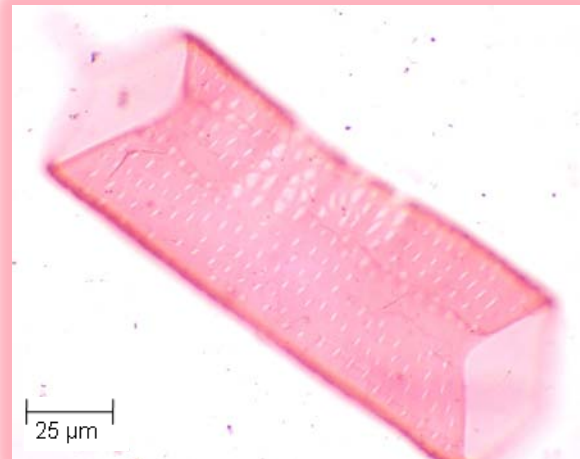
e

Plate 4.3: Length and width of tracheids in

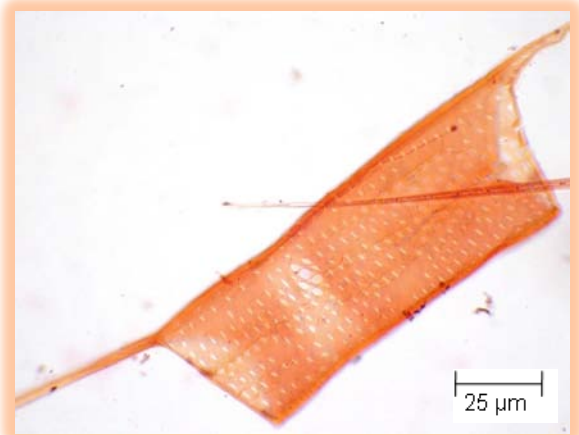
(a) *C. equisetifolia* (b) *E. tereticornis* C-10 (c) *M. azedarach* (d) *P. juliflora* and (e) *T. arjuna*



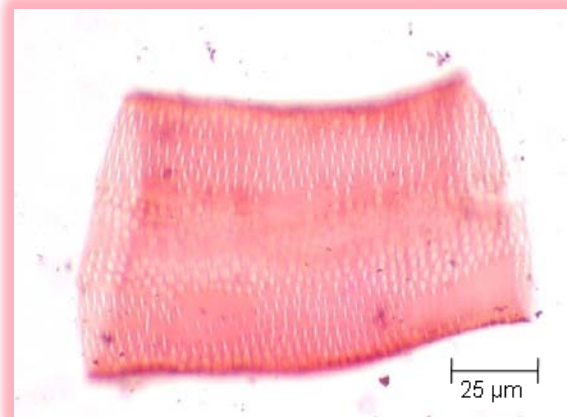
a



b



c



d



e

Plate 4.4: Length and width of vessels in

(a) *C. equisetifolia* (b) *E. tereticornis* C-10 (c) *M. azedarach* (d) *P. juliflora* and (e) *T. arjuna*

Salient findings of the experimentation are discussed in light of the available literature as follows:

5.1 A NOVEL LYSIMETER DESIGN

Physical measurement of water use by trees, which are huge modular structures and are well entrenched in the soil without any disturbance in the environmental conditions is extremely difficult. Lysimeters are accurate devices which imitate *in situ* conditions as far as possible. However, both the weighing type lysimeters (Meißner *et al.*, 2010) and drainage type lysimeters (Chhabra and Thakur, 1998) are costly to fabricate and have the problem of narrow lysimeter-to-lysimeter space due to the presence of a common working gallery between rows or clusters of lysimeters. Such structures are very suitable for low lying herbaceous plant canopies but not with trees where plant height is several meters and lateral expanse of the plants is also too much. Here, excessive tree to tree shading may impair growth and cause observational errors. For example if tree to tree spacing is to be kept 5 meters or even more (as in the present experimentation Fig. 3.3) the cemented working gallery has also to be extended causing exorbitant cost escalations. Further the RCC structure is liable to develop cracks which may cause leakage and are difficult to detect and repair. In the aforementioned background the present design of PVC based lysimeters with a provision of observation well (Fig. 3.1) is a cheaper and more practical way of measuring tree water use. In this there is no need for skilled and costly RCC masonry. The number and spacing of lysimeters can be adjusted as per requirement without any additional expenditure. At 5x5 m spacing the cost per lysimeter would be about Rs. 20000 per lysimeter for the present design and about Rs. 55000 per lysimeter for the RCC gallery design. Boman *et al.* (2007) also used similar soil embedded PVC lysimeters using 3.1x7.6 m lysimeter-to-lysimeter spacing for measuring tree water use and nutrient flux in citrus. Therefore it is concluded that present fabrication and testing of the soil-embedded PVC lysimeter with an observation well is a simple but well thought of innovative design as it permits flexible lysimeter to lysimeter spacing much desired in water use experimentation in trees. It is much cheaper than the RCC gallery-type lysimeter design.

5.2 CONSUMPTIVE WATER USE BY DIFFERENT TREE SPECIES VARIES

The comparative cumulative water drained (Fig. 4.20a, b) was 17.3 kL year⁻¹ in *C. equisetifolia*, 16.9 kL year⁻¹ in *E. tereticornis* C-10, 14 kL year⁻¹ in *P.*

juliflora, 6.8 kL year⁻¹ in *M. azedarach* and 5.9 kL year⁻¹ in *T. arjuna*.. This can also be interpreted on per day basis as 47.5 L d⁻¹ in *C. equisetifolia*, 46.2 L d⁻¹ in *E. tereticornis* C-10, 38.4 L d⁻¹ in *P. juliflora*, 18.5 L d⁻¹ in *M. azedarach* and 16.1 L d⁻¹ in *T. arjuna*. Wullschleger *et al.* (1998) who in an exhaustive review of whole-plant water use in trees enlisted 52 studies, concluded that the rates of water use ranged from 10 kg d⁻¹ (=10 L d⁻¹) for trees in a 32 year old plantation of *Quercus petraea* in eastern France to 1180 kg d⁻¹ for an over storey *Euphorbia purpurea* tree. Extreme values apart, Wullschleger *et al.* (1998) indicated maximum rates of daily water use in 90% of the observations were between 10 and 200 kg day⁻¹. It is obvious that our quantification of tree water use per day compares favorably with the available reports in literature. Even the maximum average tree water use (Fig. 4.20a, b) is about 72.5 L d⁻¹ which is substantial.

It is concluded that the maximum lysimetric tree water use was 46 to 47 L d⁻¹ in about five-year-old trees of *E. tereticornis* C-10 and *C. equisetifolia* and 38 L d⁻¹ *P. juliflora*. These species thus can be enlisted as fast biodrainers. On the other hand species like *T.arjuna* and *M. azedarach* with average daily water use in the range of 16-18 L d⁻¹ are slow or moderate biodrainers.

5.3 DIFFERENT TREE SPECIES SHOW DRASTIC FLUCTUATIONS IN WATER USE

The average water use per day apart, there is a drastic seasonal fluctuation in the daily tree water use. For example, in the year 2008-2009 (Fig. 4.19) *C. equisetifolia* showed a peak consumption of 118.8 L d⁻¹ in the month of May and lowest consumption of 8.2 L d⁻¹ in the month of February. Thus the winter transpiration was only 6.9% as compared to the summer. Likewise, the slowest biodrainer *M. azedarach* showed maximum water consumption of 43.4 L d⁻¹ during May and minimum of 6.1 L d⁻¹ during December. Chhabra and Thakur (1998) reported at Karnal (north west India) that the amount of water biodrained in about four year old *E. tereticornis* and *Bambusa arundinacea* through evapotranspiration was affected by the season being maximum in summer (April to September) and minimum in winter (October to March). It is reported in classical literature that at Nebraska, USA, (Weaver and Mogensen, 1919) and Leningrad, USSR, (Ivanov, 1924) winter transpiration of conifers was less than 1% of summer rate. Zepel *et al.* (2006) reported that an evergreen *Callitris/Eucalyptus* woodland in southeast Australia showed minimal (<1 mm/day) transpiration rates during winter as compared to very high (>3.5 mm/day) in summer. It is obvious that under the semi-arid seasonal climate obtained at Hisar (north west India, Latitude 29°10'N and Longitude 75°46'E) there would be drastic seasonal variation in the water

biodrained as well. The individual effects of seasonal factors such as temperature, sunshine hours, radiation, relative humidity etc. shall be deliberated separately in the subsequent parts of this chapter.

5.4 GREATER TREE HEIGHT ENHANCES BIODRAINAGE IN CERTAIN CASES

A comparison of Fig. 4.19 and Fig. 4.5 shows that *C. equisetifolia*, *E. tereticornis* C-10 and *P. juliflora* which had the maximum height of 690 cm, 824 cm and 374 cm respectively, in year 2009 were also the best biodrainers. The respective correlation coefficients of height with Wb in these three tree species are 0.37**, 0.27, 0.40** (Tables 4.1-4.6), respectively. Liu *et al.* (2009) also reported that under sufficient soil water supply the whole-tree transpiration in *Acacia mangium* increased in a quadric polynomial way with tree height ($P < 0.01$). Taller trees had higher references canopy stomatal conductance and higher sensitivity of canopy stomatal conductance to vapor pressure deficit compared with the shorter trees. Similarly Dalsgaard (2009) found that in tree stands dominated by *Fagus sylvatica* taller tree lots showed higher water loss as compared to the dwarf stratified parts of the canopy. Tree height *per se* increases the aerodynamical roughness of tree canopy and increases transpiration within certain limits. When tree height becomes too large, age and gravitational potential related factors may interfere and reverse the aforementioned results. For example Ryan *et al.* (2000) found that while transpiration in about 40 years old and 12 m tall old ponderosa pine trees was $0.97 \text{ mmol m}^{-2} \text{ s}^{-1}$, the rates went down to $0.57 \text{ mmol m}^{-2} \text{ s}^{-1}$ in the 290 years old and 36 m tall trees. This may explain the relatively weak correlation coefficient ($r = 0.27$) between height and Wb in *E. tereticornis* C-10 which was tallest (824 cm) yet at par with *C. equisetifolia* (690 cm), with respect to water biodrained.

5.5 GREATER STEM DIAMETER TRANSLATES TO GREATER BIODRAINAGE

Comparison of both tree girth and/or DBH (Fig.4.7, 4.8) with water biodrained (Fig. 4.19) shows that majority of the tree species having greater girth have greater biodrainage potential. This is also explicitly quantified by the correlation coefficients between girth/DBH and Wb (Table 4.1-4.6) with *C. equisetifolia* ($r = 0.37^{**}$), *E. tereticornis* C-10 ($r = 0.34^{*}$), *M. azedarach* ($r = 0.34^{*}$), *P. juliflora* ($r = 0.40^{**}$) and *T.arjuna* ($r = 0.28$) (Tables 4.1-4.6).

A plausible explanation applicable to the present observation is the greater leaf area associated with stem girth or diameter. It is very well established in literature that stem girth or diameter has an allometric relationship with above ground biomass a bulk of which is the leaf area component (Chave *et al.* 2005).

Here it would be pertinent to mention that girth/DBH also correlate positively with leaf area in *C. equisetifolia* ($r = 0.40^{**}$), *E. tereticornis* C-10 ($r = 0.62^{**}$), *M. azedarach* ($r = 0.27$), *P. juliflora* ($r = 0.39^{**}$) and *T.arjuna* ($r = 0.28$). The significance of leaf area with transpiration or biodrainage is discussed elsewhere in this chapter. Greater girth also implies greater sapwood volume which would facilitate larger volumes of water per unit time in response to the transpiration pull. Vertessy *et al.* (1995) from their studies on *Eucalyptus regnans* (mountain ash) forest concluded that stem diameter explained 93% of the variation of leaf area, 96% of the variation in sapwood area and 88% of the variation in mean daily spring transpiration. Here, it may be added that even sapwood area is known to be allometrically correlated with stem girth or DBH (Kumagai *et al.*, 2005).

5.6 LEAF AREA CORRELATES POSITIVELY WITH BIODRAINAGE

A comparison of Fig. 4.9 and Fig. 4.19 shows that leaf area (LA) has a very clear cut positive effect on tree biodrainage potential. The strong significant correlation of LA with Wb (Tables 4.1-4.6) as also reflected in correlation values of *C. equisetifolia* ($r = 0.82^{**}$), *E. tereticornis* C-10 ($r = 0.62^{**}$), *M. azedarach* ($r = 0.93^{**}$), *P. juliflora* ($r = 0.82^{**}$) and *T.arjuna* ($r = 0.61^{**}$) is also a pointer in this direction. Species like *C. equisetifolia* and *E. tereticornis* C-10 which have high leaf area values and are evergreen show the highest water use values. The significance of leaf area as a biodrainage factor is further elucidated by the deciduous species. For example *M. azedarach* which had a leaf area of 42.4 m² in the month of end July 2009 showed a biodrainage potential of 34.8 L d⁻¹, where as in the month of January 2009 the leaf area was almost nil, the biodrainage potential was 6.7 L d⁻¹ showing a % reduction of 80.7.

An even more interesting situation is encountered in the summer deciduous *T. arjuna* where the peak leaf area in the month of end July was 28.2 m² vis-à-vis biodrainage potential of 29 L d⁻¹ as compared to the leaf area values near zero in the summer month of end April vis-a-vis biodrainage potential of 12.3 L d⁻¹, showing a decline of 57.6 % in this case. This may also account for the relatively lower correlation coefficient value ($r = 0.61^{**}$) in this species as compared with the other four tree species. Dale (1992) estimated that a forest stand having a spread of one hectare displays a leaf area of 20 ha. This manifold increase in the transpiration area per unit of land area results in the increased rates of soil water drainage by the tree vegetation. Literature is replete with reports demonstrating increased transpiration or biodrainage with increasing leaf area in trees (Howard *et al.*, 1995; Chave *et al.*, 2005; Radersma *et al.*, 2006).

Another point which needs to be highlighted is that, as also enumerated in the above paragraph, even when the leaf area is nearly zero due to deciduous nature of the tree it nevertheless continues to lose considerable water into the atmosphere 8.2 L d^{-1} in *M. azedarach* in early December and 12.3 L d^{-1} in *T. arjuna* in end April. This fact indicates that even in the absence of leaves, the tree branches lose considerable amount of water in winter as well as in summer. Wittmann and Pfan (2008) reported that peridermal transpiration of stem of various deciduous trees lied in the range of 5 to 20 % of leaf transpiration.

Another angle to look at the water loss vis-à-vis leaf area is to consider the leaf area: water biodrained ratio. Taking the example of July 1-3 we get data enumerated in Table 5.1

Table 5.1: Leaf area and water biodrained ratio (LA/Wb) in different tree species

Species	Early July		LA/Wb
	Leaf area (LA) m^2	Water biodrained (Wb) L d^{-1}	
<i>C. equisetifolia</i>	82.2	74.3	1.1
<i>E. tereticornis</i> C-10	49.8	58.8	0.85
<i>M. azedarach</i>	35.0	24.3	1.44
<i>P. juliflora</i>	50.7	54.3	1.08
<i>T. arjuna</i>	25.3	22.2	1.14
Mean	48.6	46.78	1.12

It is seen that, LA:Wb ratio hovers in the range of 0.85 to 1.44. This is more particularly so in fast biodrainers i.e. *C. equisetifolia*, *E. tereticornis* C-10, *P. juliflora* where it is close to one. These trends indicate that in early July when brisk evapotranspiration conditions prevail, the LA:Wb ratio is nearly the same and leaf area is an primary determinant of Wb.

5.7 SEASONAL TEMPERATURE FLUCTUATIONS CORRELATE DIRECTLY WITH BIODRAINAGE

A careful comparison of Fig. 4.11 with Fig. 4.19 shows that in general the water biodrained (Wb) increased with increase in temperature (T) (maximum, minimum and mean) and decreased with decrease in T. The correlation coefficients (Tables 4.1-4.6) between maximum, minimum and mean with all the five tree species are highly positively significant, range of 0.64^{**} to 0.89^{**} for maximum, 0.79^{**} to 0.87^{**} for minimum and 0.75^{**} to 0.90^{**} for mean T, respectively,

indicating the domineering effect temperature has on transpiration or biodrainage. Thus, for example in case of *C. equisetifolia* when the maximum T was around 42°C in end May 2009, the Wb was 118.8 L d⁻¹ and when the T was at a minimum low 3°C in early January month the Wb was 10 L d⁻¹. It is interesting to note that T *per se* maximum, minimum or mean has a dominant effect on Wb. Our observation are in accord with Zepel *et al.* (2006) who reported minimal (< 1 mm/day) transpiration rates during winter in an evergreen *Callitris/Eucalyptus* woodland in southeast Australia showed as compared to very high (>3.5 mm/day) in summer. Even in some parts of the tropics, seasonal cycles in transpiration occur because of variations in rainfall, humidity and soil moisture.

5.8 ACTUAL VAPOR PRESSURE CORRELATES POSITIVELY WITH WATER BIODRAINED

A comparison of Fig. 4.12 and Fig. 4.19 reveals that an increase in the actual vapor pressure (Avp) (morning, evening and mean) had an increasing effect on Wb. These observations are further corroborated by the correlation coefficients (Tables 4.1-4.6). Thus the range of Avp in five tree species was 0.66** to 0.79** in morning, 0.54** to 0.69** in evening and 0.61** to 0.74** in mean. It will be worthwhile to note here that the Avp morning values have a greater magnitude of positive correlation coefficients with Wb as compared to the evening Avp. Pallardy (2008) noted that the reason evaporation and transpiration increase with increasing temperature is because the vapor concentration of water in leaves increases more rapidly than that in the unsaturated air, not as is often erroneously supposed because the relative humidity decreases. Avp is one of the agrometeorological parameter recorded as such. It's derived form i.e. VPD is a much more useful indicator and is discussed under a subsequent head in this chapter.

5.9 NO TRENDS ARE REFLECTED BETWEEN RELATIVE HUMIDITY AND WATER BIODRAINED

A careful consideration of Fig. 4.13 and Fig. 4.19 along with Tables 4.1-4.6 indicates relative humidity (RH) have a complex interaction with Wb. We shall first consider the fact that peak values of Wb both in May 2008 and 2009 in all the tree species are obtained when the mean RH during this period is at a low of about 25%. However, these trends are not maintained subsequently due to weird values of RH. Thus, RH is about 60 % during December 2008 (62.8) as well as in June 2009 (60.0). Therefore, correlation coefficients of RH morning, evening and mean vary from -0.26 to -0.67** in morning, -0.03 to 0.28 in evening and 0.04 to -0.36** in mean, respectively, in all the five tree species. The only consistent trend in this data is the negative correlation of RH morning with Wb which is understandable as

barring the months of April and May, morning RH remains 70-95% resulting in low evapotranspiration. Based on their observations on road side trees of *Quercus myrsinaefolia*, Huang and Ooka (2010) also concluded that the influence of RH of air on the total amount of transpiration was not significant. Nevertheless, consideration of RH is extremely important. This is explained under the subsequent head of VPD.

5.10 VAPOR PRESSURE DEFICIT CORRELATES POSITIVELY WITH WATER BIODRAINED

The data presented in Fig. 4.14 as compared with Fig. 4.19 considered along with correlation coefficient Tables 4.1-4.6 clearly indicates that vapor pressure deficit (VPD) has consistent positive significant correlation in the range of 0.43** to 0.80** in different tree species. As also pointed out in earlier section of this thesis, a straight forward consideration of factors like T, Avp and RH on Wb or evapotranspiration may be misleading on occasions due to the complex interaction of these factors with each other. Thus VPD is an upgrading over RH alone as the former takes into consideration of the water holding capacity of air which roughly doubles with every 11.4⁰C increase in T (Muller and Lambs, 2009). Morris *et al.* (2006) also found that day time transpiration in *Eucalyptus camaldulensis* trees at Pucca Anna, Pakistan was linearly correlated with VPD.

5.11 HIGH WIND SPEED LEADS TO HIGHER TRANSPIRATION

Data presented in Fig. 4.15 shows that by and large episodes of high wind speed (WS) characteristically takes place in the months of end April to end July. These periods are also characterized by high values of Wb (Fig. 4.19). These observations are further authenticated by the high positive correlation with WS and Wb in the range of 0.65** to 0.81** in the five tree species (Tables 4.1-4.6). Xu *et al.* (2006) found that pan coefficient (ratio of evapotranspiration to pan evaporation) is significantly influenced by wind speed and relative humidity in the Changjiang (Yangtze River) catchment area of China. Higher values of the pan coefficient were found in the central area of the catchment with a relatively high humidity (as compared with the upper area) and a very low wind speed (as compared with other areas).

5.12 SUNSHINE HOURS DO NOT CORRELATE WITH WATER BIODRAINED

The longest day of about 14 hrs at Hisar (Latitude 29°10'N and Longitude 75°46'E) is obtained on 21st June and the shortest day of about 10.5 hrs is obtained on 22nd December. However, as seen from the scatter of the sunshine hours (Fig. 4.16) obtained during the period of August, 2007 to August, 2009 no such temporal gradient of sunshine hour prevails at Hisar. This trend is amply reflected as a weak

non significant correlation between SH and Wb in the range of 0.07 to 0.26 (Table 4.1-4.6) in the five tree species. This behavior is explained due to the erratic and intermittent local climatic cloudiness during the summer months (particularly monsoon months). Even during the winter when the day lengths are short, episodes of fog and cloudiness make the actual sunshine hours very erratic. The annual cycle of sunshine definitely contributes to the overall insolation or radiation that causes broad seasonal than local climatic effects.

5.13 HIGH INCIDENT RADIATION CAUSES HIGH WATER BIODRAINED

It is seen from Fig. 4.17 that there is a considerable increase in the incident radiation (Rad) during the summer months of May and June when it was in the range of 3051-3089 J cm⁻² d⁻¹ and decrease in the month of mid December to January when it was in the range of 2253-2276 J cm⁻² d⁻¹. The higher summer values of radiation are due to longer daylengths/sunshine hours as well as the summer angle of sun rays at noon with earth's horizontal being close to 90° in contrast to winter when sunshine hours are shorter and the angle is far less than 90° or oblique even at noon. Within this range a slight decline in the Rad during July to September is due to cloudiness of wet season (kharif) is also seen. Higher incident radiation by and large increases the T and vice-versa. The positive correlation of T and related factors with evapotranspiration or Wb has already been discussed in this section of thesis. The significant positive correlation of Rad with Wb (Fig. 4.2) in the range of 0.16 to 0.65** (Table 4.1-4.6) further asserts these arguments. Huang and Ooka (2010) found that transpiration of road side trees *Quercus myrsinaefolia* was most significantly influenced by solar radiation or photosynthetically active radiation, followed by the leaf or air temperature. Our results on the role of Rad on transpiration or Wb assume significance in light of the hypothesis put forth by Pieruschka *et al.* (2010) who reexamined the transpiration based hydrological cycle and attributed a domineering role of radiation in the process of transpiration. They ruled out the current concepts of stomata-based control of transpiration. It was suggested there is a radiation controlled rate of vapor production in the leaf interior that governs transpiration. Thus unlike imposed evaporation where water vapor is pulled from a wet surface by a diffusion gradient, in equilibrium evaporation water vapor is pushed into the surrounding air by the input of heat.

5.14 POTENTIAL EVAPORATION HAS A STRAIGHT FORWARD POSITIVE CORRELATION WITH WATER BIODRAINED

Potential evaporation (Ep) is a measure of evaporation from the exposed water surface into the atmosphere encompasses all the afore discussed parameters like T, Avp, VPD, RH, Rad etc. that have a direct bearing on evapotranspiration or

Wb. It is therefore not unexpected those higher values of Ep (Fig. 4.18) coincide with Wb (Fig. 4.19) of different tree species. These trends are also confirmed by the significant positive correlation in the different lysimeter grown tree which is in the range of 0.56** to 0.91** (Table 4.1-4.6). Xu *et al.* (2006) carried intensive reference evapotranspiration versus pan evaporation studies in Changjiang (Yangtze River) catchment area of China and concluded that spatial distributions of reference evapotranspiration and pan evaporation are roughly similar. They also found that spatial correlation coefficient between the reference evapotranspiration and pan evaporation are high both for the seasonal and annual values.

5.15 TEMPERATURE, LEAF AREA AND VAPOR PRESSURE ARE AMONGST MOST IMPORTANT FACTORS CONTROLLING WATER BIOTRANSPIRATION

Regression equations were worked out in all the five tree species to delimit the effects of different factors in Wb.

5.15a. In *C. equisetifolia* the best fit model for estimation of Wb based on single environmental parameters i.e. mean T is expressed as

$$Wb = -50.307 + 4.047^{**}(T \text{ mean}) [r^2 = 0.78]$$

78% variability in Wb is explained by mean T. The r^2 values are significant at $P < 0.01$

With the addition of biological parameter i.e. with the addition of girth in this model, the predictability of the model was improved by 10% i.e. 88%.

$$Wb = -99.378 + 3.958^{**}(T \text{ mean}) + 2.180^{**}(\text{Girth}) [r^2 = 0.88]$$

The model based on three parameters T mean, girth and WS explained the maximum variability in Wb upto 91%.

$$Wb = -91.604 + 3.119^{**}(T \text{ mean}) + 1.997^{**}(\text{Girth}) + 3.508^{**}(\text{WS}) [r^2 = 0.91]$$

5.15b. In *E. tereticornis* C-10 the Ep rate accounted for the variation in the Wb upto 82%.

$$Wb = 7.439 + 8.407^{**}(\text{Ep}) [r^2 = 0.82]$$

The accuracy of the model can be improved by including mean AVP i.e. 90%.

$$Wb = -3.712 + 7.311^{**}(\text{Ep}) + 1.083 (\text{Avp mean}) [r^2 = 0.90]$$

EP, AVP and height collectively explain the variation in the Wb upto 95%.

$$Wb = -22.453 + 7.143^{**}(\text{Ep}) + 1.098^{**}(\text{Avp mean}) + 0.031^{**} (\text{Height}) [r^2 = 0.95]$$

5.15c. In *M. azedarach*, the best fit model for estimating Wb based on biotic parameters is expressed as

$$Wb = 6.087 + 0.668^{**}(LA) [r^2 = 0.86]$$

LA explained the 86% variability in Wb. The r^2 values are significant at $P < 0.01$.

The predictability of model was improved by 5% with the addition of abiotic factor i.e. Ep

$$Wb = 2.503 + 0.461^{**}(LA) + 1.616^{**}(Ep) [r^2 = 0.91]$$

$$Wb = -4.099 + 0.421^{**}(LA) + 1.728^{**}(Ep) + 1.077^{**}(DBH) [r^2 = 0.93]$$

However, with the addition of biological factor of height after the addition of DBH the accuracy was improved only upto 1%.

$$Wb = 24.003 + 0.402^{**}(LA) + 1.731^{**}(Ep) + 3.808^{**}(DBH) - 0.222^{**}(Height) [r^2 = 0.94]$$

- 5.15d. In the case of *P. juliflora* a simple model based on mean T explains the variability in Wb upto 74%

$$Wb = -27.236 + 2.722^{**}(T \text{ mean}) [r^2 = 0.74]$$

The accuracy of this model is improved with the addition of height and Rad to 87%

$$Wb = -56.601 + 2.625^{**}(T \text{ mean}) + 0.113^{**}(Height) [r^2 = 0.84]$$

$$Wb = -25.008 + 2.948^{**}(T \text{ mean}) + 0.121^{**}(Height) - 0.016^{**}(Rad) [r^2 = 0.87]$$

With the further addition of LA in this model the accuracy was improved by 1% only and 12% remained unaccounted for.

$$Wb = -10.590 + 2.948^{**}(T \text{ mean}) + 0.097^{**}(Height) - 0.018^{**}(Rad) + 0.223^{**}(LA) [r^2 = 0.88]$$

- 5.15e. In *T. arunja*, the T mean accounted for the variation in Wb upto 56%.

$$Wb = -5.633 + 0.899^{**}(T \text{ mean}) [r^2 = 0.56]$$

While considering the *T. arjuna* it was found that there was 24% increment in the accuracy of Wb when LA was further added after the temperature mean i.e.

$$Wb = -13.069 + 0.797^{**}(T \text{ mean}) + 0.526^{**}(LA) [r^2 = 0.80]$$

Further the contribution of DBH alongwith EP in further enhancement was only 2%.

$$Wb = -22.079 + 0.773^{**}(T \text{ mean}) + 0.529^{**}(LA) + 1.658^{**}(DBH) [r^2 = 0.85]$$

$$Wb = -20.793 + 0.476^{**}(T \text{ mean}) + 0.611^{**}(LA) + 1.642^{**}(DBH) + 0.964^{**}(Ep) [r^2 = 0.87]$$

Having overview of the afore discussed regression models in the five tree species it is generalized that the factors that dominate the biodrainage/ evapotranspiration in decreasing order of influence are temperature, leaf area/potential evaporation, vapor pressure, wind speed, radiation and tree height.

5.16 DIFFERENT PHYSIOLOGICAL PARAMETERS VARIOUSLY INFLUENCE BIODRAINAGE

As already mentioned transpiration rates (Fig. 4.22) and stomatal conductance (Fig. 4.23) were higher in fast biodrainers like *C. equisetifolia*, *E. tereticornis* C-10 and *P. Julliflora*. Likewise, stomatal density of *C. equisetifolia* was also the highest (Fig. 4.27). Oren *et al.* (2001) reported that water use, as indicated by and xylem sap flux, in a flooded stand of *Taxodium distichum* was correlated with transpiration rate per unit of leaf area. Tang *et al.* (2006) also provided evidence that sap flux reflected canopy transpiration, stomatal conductance and water use efficiency in *Acer saccharum*, *Betula alleghaniensis* and *Tsuga canadensis* forest in the Great Lakes region of the United States.

PWL also recorded higher values in species like *C. equisetifolia* and *E. tereticornis* C-10 as compared to the slow biodrainers (Fig. 4.26). This fact is understandable as greater potometric loss values clearly indicate propensity of the shoot system for greater water loss or biodrainage potential. This is also indicated by other potometric studies in trees (Roberts, 1978; Vertessy, 1977; Gutierrez and Santiago, 2006).

It is also noted that parameters like RWC appear to have no direct effect on the Wb. This behaviour should be understandable in light of the fact that observations in all the tree species were made in a water saturated environment and this did not reflect as highly contrasting values of RWC within the species.

Similarly in case of dimensions of the tracheids and vessel elements, a straight forward association with biodrainage potential seems to be lacking. Thus for example the widest tracheids were found in *T. arjuna*, widest vessels in *P. juliflora*, longest tracheids in *E. tereticornis* C-10 and longest vessel elements in *T. arjuna* (Fig. 4.28, 4.29). Carlquist (1975), reported that vessel elements in Onagraceae correlated perfectly with groups of species; elements are long and wide in mesomorphic species, shortest and narrowest in the most xeromorphic species. Pallardy (2008) observed that in angiosperm, wide vessels, long vessels and numerous vessels are associated with high specific conductivity. Strictly from a hydraulic perspective it would appear that xylem should contain just a few very larger vessels obviously more critical studies are needed to resolve the nuances of sapwood element characteristics and tree water use.

5.17 CONCLUDING REMARKS AND FUTURE PROJECTIONS

The demonstrated use of a lysimetric system with novel features of the incorporation of an ‘observation’ well that makes the set up relatively cheap and gives quick and straight forward results on Wb of five tree species has been demonstrated. This design should prove helpful in more extensive studies involving a range of tree species from the point of view of Wb. The lysimetric design can also be used for other experimental objectives in soil science, forestry and environmental studies as indicated in section 2.2.2 and Table 2.1 of this thesis.

We have demonstrated delimitation of five tree species into fast biodrainers as well as slow biodrainers. The fast biodrainers like *E. tereticornis* have a biodrainge potential of 46.23 L d^{-1} as compared to slow biodrainers like *T. arjuna* that has a biodrainge potential of 16.15 L d^{-1} . What use such information can have for biodrianage and related soil water issues?

As also pointed out in Introduction chapter of this thesis, a land locked inland basin of the districts Jhajjar-Rohtak-Hisar-Fatehabad-Sirsa exists in the state of Haryana where the rise of poor quality water table is an issue. On a seasonal scale pinch of this problem is felt in the post monsoon season when water logged conditions damage the kharif crops and even the sowing of rabi crops such as wheat are threatened (Anonymous, 2010). It is in this landscape the usefulness of fast biodrainers like *Casuarina* and *Eucalyptus* shall be paramount. On the other hand, it is also pointed out in the section 2.1.2 that in Northern Haryana vertical drainage of the good quality ground water over a prolonged period of time has led to the water table falling to abysmally lower depths and the bore wells turning dry. This has resulted in the creation of ‘dark zones’ in the districts of Karnal, Kurukshetra and Kaithal (Anonymous, 2009). Should the fast biodrainers like *E. tereticornis* be planted here? This is more particularly so when the *Eucalyptus* species have the demonstrated capacity to strike sinker roots as deep as 20 m to access the water table (section 2.3.5). Are these species not adding to the existing ecological crises? It is here that the role of slow biodrainers like *Terminalia* and *Melia* becomes vital. As also discussed these species are deciduous and in certain seasons, the biodrainage potential becomes very low due to the total lack of foliage. Here, we emphasize the role of species like *T. arjuna* which are early summer deciduous. Considering the peak values of water biodrained with respect to the species *T. arjuna* depicts peak values of 31.3 L d^{-1} in the month of September is strong contrast to all other species which depict the peak values in the month of May (Fig. 4.19). Thus, early summer deciduous species like *T. arjuna* (and many more like *Ficus* and *Cassia*) stand out as efficient water savers in the water starved areas discussed before.

In strong contrast to species like *Casuarina*, *Eucalyptus*, *Terminalia* and *Melia*, *Prosopis juliflora* is a highly invasive species that has a unique self-colonizing ability and has established it-self in all abandoned lands infested with waterlogging and salinity. Considered as weed by some *Prosopis* as a matter of fact is useful for local communities as fuel wood and fencing material (Dutton, 1989). As demonstrated in present studies *P. juliflora* is a fast biodrainer. It is opined that species like *P. juliflora* act as natural block biodrainage plantations that have a crucial role in checking the excessive water tables of this region. The exact ecophysiological role of naturally occurring populations of species like *P. juliflora* is a matter of further investigation.

Present investigation “Lysimetric studies on some tree species to evaluate their biodrainage potential” was carried out with the objective of assessing the comparative biodrainage potential of five tree species and to have an insight into the tree growth, physiological and environmental factors that influence transpiration (biodrainage). Five tree species i.e. *Casuarina equisetifolia*, *Eucalyptus tereticornis* clone-10, *Melia azedarach*, *Prosopis juliflora* and *Terminalia arjuna* were grown in specially fabricated field-soil-filled lysimeters (2.84 m³) and observations were made when these were about 3½ years old in the adult phase. Water biodrained and related tree growth and physiological parameters were recorded for a period of two years i.e. August 2007 to August 2009. Salient conclusion-oriented findings are as under:

- The fabrication of PVC-based lysimeters with the provision of an observation well and its testing to determine the biodrainage potential of different tree species was done. This lysimetric design is simple, can be installed without much civil engineering knowledge and the requirement of a working gallery is done away with in its design. Thus the tree to tree spacing can also be extended in this case to any distance (5 m in the present case) without any additional cost.
- Consumptive water use by trees like *C. equisetifolia*, *E. tereticornis* C-10 and *P. juliflora* was in the range of 14 to 17 kL year⁻¹ and these were designated as fast biodrainers. The use of such tree species is recommended in the biodrainage plantations of water logged areas in south Haryana.
- Conversely, water biodrained potential of trees like *M. azedarach* and *T. arjuna* was 5.9 and 6.8 kL year⁻¹, respectively. Species like *T. arjuna* are summer deciduous and its biodrainage potential in May was low (15.8 L d⁻¹) as compared to the peak values of 31.3 L d⁻¹ in September. These trees were designated as slow biodrainers and their plantation is recommended in the ‘dark zones’ of north Haryana where the sweet water table is very low.
- Tree growth parameters such as tree height and girth at breast height (GBH) had a moderate influence on increasing tree biodrainage. However, leaf area had a significant positive correlation with water biodrained, as indicated by correlation coefficient values $r = 0.816^{**}$ in *C. equisetifolia*, 0.624^{**} in *E.*

tereticornis C-10, 0.928** in *M. azedarach*, 0.823** in *P. juliflora* and 0.613** in *T. arjuna*. Development of large leaf area by the tree species is identified as a major tree growth parameters having prominent effect on biodrainage.

- Amongst the abiotic factors, temperature, actual vapor pressure and vapor pressure deficit with r in the range of 0.750** to 0.902**, 0.610** to 0.741** and 0.434** to 0.797**, respectively, in the different tree species were the most influential factors determining quantity of water biodrained. It is concluded that ambient temperature (due to overall radiation influx) controls transpiration or water biodrained in the most domineering way in contrast to all other factors. Greater wind speed also contributed significantly ($r = 0.645**$ to $0.812**$) towards water biodrained.
- Pan or potential evaporation had an overall positive correlation with W_b in all the tree species. It is an excellent parameter to predict the extent of conduciveness of all the environmental factors put together vis-à-vis biodrainage.
- Interestingly, factors like sunshine hours ($r = 0.264$ to 0.072) and relative humidity ($r = 0.037$ to -0.363) appear to contribute a little towards W_b when their values are considered as such. However, their subtle contribution towards W_b should not be underestimated.
- Amongst various physiological traits, transpiration, stomatal conductance, potometric water loss and stomatal density appear to contribute positively towards transpiration.
- Parameters like relative water content did not appear to contribute towards biodrainage. This is probably because of the water-saturated environment in which the trees were grown and tested for this trait.
- The dimensions (length and breadth) of the water conducting elements tracheids and vessels did not appear to have a direct bearing on the water biodrained. It is opined that their water conductivity must have a role in the sap flow of the tree stem, but this needs to be looked more intensively in terms of the total sapwood volume as well.

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ABSTRACT

Title of Thesis : Lysimetric studies on some tree species to evaluate their biodrainage potential
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Twenty four PVC soil-filled (2.84 m^3) lysimeters fitted with an 'observation well' pipe with a provision to maintain and observe water table at about 90 cm from the soil surface were fabricated to quantify tree water use or biodrainage. Five tree species i.e. *Casuarina equisetifolia*, *Eucalyptus tereticornis* clone-10, *Melia azedarach*, *Prosopis juliflora*, *Terminalia arjuna* were planted (four lysimeters for each species) in these lysimeters. Four lysimeters were kept fallow to act as control. The difference between water lost from tree lysimeter system (evapotranspiration) and control lysimeters (evaporation) gave the values of actual water transpired or the water biodrained. Different tree growth parameters viz. height, girth, diameter at breast height (DBH), leaf area (LA) and environmental parameters viz. temperature (T), actual vapor pressure (Avp), vapor pressure deficit (VPD), wind speed (WS), radiation (Rad) and potential evaporation (Ep) were also measured for a period of two years (August 2007 to August 2009). The results established a clear average trend of low biodrainage (Wb) in the winter months of December-January ($7 \text{ to } 9 \text{ L d}^{-1}$), followed by rapid increase during the spring season of March-April ($12 \text{ to } 44 \text{ L d}^{-1}$). All time high average values of Wb were obtained in dry summer in May ($45 \text{ to } 60 \text{ L d}^{-1}$). In the wet summer months of July to September, the Wb average was relatively less ($42 \text{ to } 53 \text{ L d}^{-1}$) as compared to May. In autumn season of end September to early October Wb was modest and declined further in November ($21.5 \text{ to } 30.2 \text{ L d}^{-1}$), to again reach the lowest values in the winter. However, tree species differed in their individual Wb potential which followed the trend: *C. equisetifolia* (47 L d^{-1}) $\approx$ *E. tereticornis* C-10 (46 L d^{-1}) $>$ *P. juliflora* (38 L d^{-1}) $>$ *M. azedarach* (18 L d^{-1}) $>$ *T. arjuna* (16 L d^{-1}) $>$ control (1 L d^{-1}). *C. equisetifolia*, *E. tereticornis* C-10 and *P. juliflora* were thus designated as fast biodrainers whereas *M. azedarach* and *T. arjuna* were designated as slow biodrainers. Data analysis of various tree growth and environmental factors showed that the most domineering factors that control biodrainage were LA ($r = 0.613^{**}$ to 0.928^{**}), mean temperature ($r = 0.750^{**}$ to 0.902^{**}), mean Avp ($r = 0.610^{**}$ to 0.741^{**}), VPD ($r = 0.434^{**}$ to 0.797^{**}), WS ($r = 0.645^{**}$ to 0.812^{**}) and Ep ($r = 0.557^{**}$ to 0.906^{**}). Curiously enough factors like relative humidity and sunshine hours did not correlate positively with biodrainage. Different biodrainage traits [relative water content (RWC), leaf water potential (LWR), transpiration (E), stomatal conductance (g_s), potometric water loss (PWL), tracheid (length and width), vessel (length and width) and stomatal density] of the tree species were also studied to correlate with their Wb. It was observed that in species like *C. equisetifolia*, *E. tereticornis* C-10 which were efficient biodrainers, transpiration rates, stomatal conductance and potometric water loss were also higher, whereas the effect of factors like RWC, LWR, stomatal density, length and width of tracheids and vessels did not appear to have a consistent trend with Wb. It is concluded that, tree species like *C. equisetifolia*, *E. tereticornis* C-10 and *P. juliflora* are efficient biodrainers because of their capability to develop and display higher leaf area which has the propensity to lose water due to higher stomatal conductance and transpiration rate in the advent of environmental factors like high ambient temperatures, vapor pressure deficit and wind speed.

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M.Sc.	CCS HAU, Hisar	2006	72.30%	Major : Plant Physiology Minor : Biotechnology & Molecular Biology
B.Sc.	Kurukshetra University, Kurukshetra	2004	64.89%	All Medical Subjects

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(l) Medals/Honours received : –
(m) List of Publications : –

- Acclimatory response to hydrogen peroxide and glutathione under salt-boron stress through their impact on mineral nutrition and antioxidant defense system in pigeonpea (*Cajanus cajan* L.). *Physiol Mol Biol Plants* (July–September 2010) **16**(3):295–304.
- Physiological behaviour vis-à-vis water logging conditions in some tree speices. *Indian J. Plant Physiol.* Vol. 15, No. 1 pp: 44-53 (Jan.-Mar, 2010).

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