ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

Studies on Some Drought Resistance Characteristics of Wild Coffee Populations

By

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V. List of abbreviations

ΔF/Fm′= (F-Fm')/Fm'= Effective quantum yield of a light adapted leaf (chlorophyll fluorescence yield)

B= Bonga

BL= Bale

COCE= Conservation and use of the Wild Populations of *Coffea arabica* in the Montane Rainforests of Ethiopia

EARO= Ethiopian Agricultural Research Organization

ETR= Electron Transport Rate

F= Minimal Chlorophyll Fluorescence of a light adapted leaf

Fm'= Maximal Chlorophyll fluorescence of a light adapted leaf

FRC= Forestry Research Center

LWP=Leaf Water Potential

PAM= Pulse Amplitude Modulation

PAR= Photosynthetically active radiation

PMS= Plant Moisture Stress

S=Sheko

SM= Soil Moisture

SWP= Soil Water Potential

Y= Yayu

ZEF= Center for Development Research

ABSTRACT

Volumetric soil water content, soil water potential (SWP), leaf water potential (LWP) and chlorophyll fluorescence were measured to evaluate physiological responses and adaptability to water deficits in the wild arabica coffee populations along climatic gradients in the southeastern (SE), South and Southwestern (SW) of Ethiopia. The sites selected were Harena (Bale) forest from the SE, Bonga and Sheko forests from the South and Yayu forest from the SW regions. Each of the four sites was sub divided in to three sub sites that represent different coffee accessions (sub populations or land races). Therefore, a total of 12 coffee accessions or sub populations were studied in situ.

The soil moisture at two distances from the individual coffee trees, wet and dry soil moisture contrasts as well as diurnal variations were measured and analyzed. At the same time, soil moisture deeper than the surface layer was also measured. The measurement of soil water potential took place at three depths during the wet season but at one depth in the dry season. In the case of leaf water potential, both predawn and midday as well as diurnal changes were recorded in the dry season but only midday values were recorded in the wet season.

Diurnal chlorophyll fluorescence yield and light responses were measured for light adapted leaves. Comparisons were made between leaves of three age groups (older, medium aged and younger), wet and dry seasons as well as shade and sun exposed coffee trees.

The wet season in Bale differs from that of the three sites (Bonga, Sheko and Yayu). It was dry in Bale during the two periods of measurements. Therefore, wet-dry comparison does not include Bale. Almost similar soil moisture content and soil water potential values were found in Bonga, Sheko and Yayu during the wet season. But considerable variation was found in most of the subsites during the dry season and maximum and minimum values were recorded in Bonga 2 and Sheko 3 respectively. When the soil moisture values of all the sites were compared based on the mean values of their sub sites, Bonga and Yayu had the highest and lowest soil moisture content in the dry season, respectively. Minimum and maximum range of wet and dry seasons' soil

moisture content was also found in Bonga and Yayu respectively. Bonga had the highest predawn leaf water potential (LWP) followed by Yayu. The highest and the lowest Midday LWP values were recorded in Bonga and Sheko respectively. The highest and the lowest diurnal ranges of LWP were recorded in Yayu and Bale respectively. Based on their LWP values, Yayu and Sheko coffee populations seem to be drought avoiders (by higher re-saturation capacity) whereas, Bale coffees seem to be drought tolerant. Most probably, in Bonga (the wettest site), the coffee populations were not too stressed to display some drought resistance mechanisms. Significant difference was found between the wet and dry seasons' midday LWP values.

Chlorophyll fluorescence yield of coffee leaves of different age groups did not show significant difference (P=0.05). But Chlorophyll fluorescence yields of most of the sites and sub sites were significantly different (P=0.05). Higher value of fluorescence yield was found in the dry season than the wet season. Shade coffees had higher values of fluorescence yield than sun exposed coffees. The fluorescence yield was linearly and weakly correlated to both soil moisture and LWP but the correlation to leaf water potential was relatively higher. A linear, somewhat strong correlation was found between soil moisture and leaf water potential. The strongest correlation was found between soil moisture content and soil water potential. The grand mean soil moisture of all the coffee forests for the wet and dry seasons were 47.91% and 17%, respectively. Concerning the sub sites, the highest level of stress was found in Sheko 3and the lowest in Bonga 2, whereas among the sites, the highest level of stress was found in Sheko and Yayu and the lowest in Bonga for the dry season.

1. INTRODUCTION

1.1 Background

Coffea arabica is indigenous to the tropical rain forests of Ethiopia in the South and Southwest where there was persistent usage since ancient times (Purseglove, 1974b; Cobley, 1976; Teweld-Birhan Gebregzabiher, 1978; Kochhar, 1981; Masresha Fetene and Solomon Habtamariam, 1995; DaMatta, 2004). The name coffee was taken from the Ethiopian province 'Kafa' or 'Kefa' (ZEF and COCE, 2002). The indigenous Ethiopian wild coffee (*Coffea arabica*) was discovered about AD 850 (may be a century before according to Robinson, 1995) and was cultivated in Harar province and spread to Meca and different Islamic world (Smith, 1987). Moore *et al.*, (1995) suggested coffee to have been used more than one thousand years ago and they indicated that it was used as food mainly for source of protein, medicine and beverage. In Ethiopia coffee has been used as a stimulant drink by different tribes from ancient times (Yohannes Uloro, 1985).

The arabica coffee accounts for 90% of world's cultivation because of its superior qualities including less caffeine content (Purseglove, 1974b; Cambrony, 1992). The estimated chemical composition of dried *C. arbica* beans is 12% water, 13% protein, 12% fat, 9% sugars, 1-1.5% caffeine, 9% caffetanic acid, 5% other soluble substances, 35% cellulose and other allied substances and 4% ash (Purseglove, 1974b; Cobley, 1976).

At present, *Coffea arabica* is cultivated in the different parts of the world as well as in its place of origin and diversity, Ethiopia. The arabica coffee growing countries are South and Central America, Caribbean Islands in the Pacific; India, Indonesia, Vietnam, New Guinea, the Philippines, high land areas of Africa; Kenya Tanzania, Zimbabwe, Rwanda, Burundi, Zaire, Angola and Cameroon (Cambrony, 1992).

Arabica coffee is the only tetraploid (2n=4x=44) and self-fertile species of the genus *Coffea* while all other species of the genus are diploid (2n=2x=22) and self-infertile (Scherrw and Rutten, 1981; Berthouly and Etiere, 2000; Lasherms *et al.*, 2000). This means that it has four complete sets of chromosomes. In normal diploid species, one of the two sets of chromosomes is inherited from the male parent and the other set from the female parent. It is believed that arabica coffee originated from two diploid wild ancestors: *C. canephora* and *C. eugenoiodes* or *ecotypes* related to these species and only the Ethiopian tropical climate was suitable for its successful viability and fitness as an interspecific hybrid (hybrid between two distinct species) where it was diversified (Rutten, 1981; Robinson, 1995; Lashermes *et al.*, 2000).

1.2 Coffee Ecology

In Ethiopia, arabica coffee grows at various altitudes with preference to the upland wet forests between 1000-2200 m between 6-9^{o}N and 34-40^{o}E in the regions of Wollega, Gamu-Gofa, Illubabor, Kefa and Hararge (Purseglove, 1974b; Cobley, 1976; Yohannes Uluro, 1985; Tadesse Woldemariam, 2003; STCP, 2004). It requires cooler climates and a mean temperature of about 20-22^{o}C (Williams and Chew, 1979). It can be grown where the dry seasons are not too long and the soil has a high water retention capacity, where the average total rainfall is at least 1100 mm (Hornack, 1998).

Temperature and rainfall are the most important factors for coffee growth. It can adapt successfully to excessive rainfall if the topography and the physical characteristics of the ground allow for adequate drainage (Cambrony, 1992). It was indicated that temperature above optimum facilitates rapid growth, too early bearing, over bearing, early exhaustion, dieback and disease attack.

Coffee can easily adapt to different soil types and the soil requirements for sustainable high yield of arabica should be of deep profile, over about 180 cm, moderately to heavy texture, good drainage and of high organic matter content (Cobley, 1976; Cambrony, 1992). They pointed out that the soil conditions together with other climatic conditions preferable for coffee growth should be that restrict vegetation growth so that overbearing is avoided and the crop continues from season to season. Sandy and shallow soils are not desirable for coffee growth (Opeké, 1992).

The soils of managed coffee require continuous follow-up and maintenance by growers since coffee exhausts the soil easily (Costé, 1992). It is possible to improve the soil fertility using organic or inorganic fertilizers for sustainable productivity (Williams and Chew, 1979; Cobley, 1992; Subian, and Akal, 2000; Abeles, 2000). The organic fertilizers come from mulching (covering the soil surface with fallen plant materials like leaves and slashed weeds), green manure (growing of some legumes which are prematurely hoed to be decomposed) and processed coffee wastes (coffee husks and pulp). The requirement and supply of mineral fertilizers (inorganic fertilizers) need careful evaluation and analysis of the soils and/or the plants to see the mineral nutrients that were already depleted.

1.3 Some ecological constraints related to wild coffee in Ethiopia

Arabica coffee naturally exists in the montane rainforests of Ethiopia in the south and southwest as a wild understorey species. The wild arabica coffee makes part of the forest coffee ecosystems which host diverse living communities. However, the genetic resources of these forests, including the arabica coffee are disappearing due to deforestations (STCP, 2004). This human impact (deforestation in general) on the natural forests is threatening the arabica coffee species population from time to time (Tadesse, *et al.*, 2002; Thompson and Sheffy, 2004). Parts of the forests are being converted into coffee plantations, garden coffee and farmland for the cultivation of other crop plants as well. As far as a patch of the forestland is converted to farmland, there is loss of many plant species including wild coffee that is nowadays becoming the main threat to the natural forest ecosystems. In general, the montane rainforests have a wide range of wealth in terms of species diversity and exist with the highest ecological complexity; thus a single clearance of a small area may result in destruction of many species (Maydell, 1990; Vexkiill and Mufert, 1990).

Many authors recommend different conservation practices that can reduce the loss of the wealth of these major ecological regions (Vexkill and Mufert, 1990; Coste, 1992). Digby and Cruti (1999); Girardin *et al.*, (1999); Okoji and Moses (1999) recommend consideration of environmental impacts of farming systems, agroforestry systems and strong improvement of the links between small-scale holders and agroindusrty whereas Tadesse Woldemariam (2003) recommended *in situ* conservation of specially the natural coffee forests. The ecological crisis due to deforestation of the natural forestlands, which could end up in the permanent loss of wild germplasm, like coffee, could be controlled by giving priority to agroforestry practices and establishment and maintenance of sustainable agriculture so that penetration of the people into the forests is minimized (Ruf, 1992). It is also good strategy to pay special attention to the links between the physical resources, the livelihood systems of the poor households and the appropriateness of different agricultural technologies (Redclift, 1990; Maydell, 1990).

The attraction to the natural ecosystem by the people living close to it can be seen from different interrelated reasons. First of all, the economic standard of the people is extremely low which puts their demand into an imbalance utilization of the forest products. The poor economy would not allow them to maximize productivity from the very plot of land they have. Secondly increased human population also puts a great demand to more productive land, hence the conversion of a great deal of forest land into farm land. Thirdly, the forestland becomes more fertile and productive than the land that was used for a long period of time when it is first converted in to farmland. This does not mean that the land remains fertile for long period of time. It is more likely that the soil will be depleted shortly in three to four years. Fourth, the managed coffees produce more crops than the unmanaged ones because management practices allow the coffee to get enough light which is a problem in natural forest conditions. The people living nearby the forests inevitably utilize some of the forest products which may include firewood consumptions from fallen twigs and dried branches, local constructions from wood trees and climbers, wild coffee crops and some spices. The forests also offer grazing of the domestic animals. There are different levels of management of the natural coffee forests. In some of the accessible forests, the people simply go to the forests to pick the fruits during the time of ripening. Any one can do that and there is no problem of ownership. On the other hand, some of the wild coffee populations have fallen under the ownership of the farmers. In such forests the farmers exercise some management practices in order to get good harvest from the coffee populations. The coffee populations are still in their wild state except that the farmers to some extent control weeds and shade trees to get good yield. The farmers are not allowed to introduce new varieties or hybrids to the indigenous coffee populations so that the naturalness of the coffee populations that exist there would not be questioned.

1.4 Shade preference of coffee

Coffee is a shade tolerant understorey species that grows either without shade, with temporary shade or with permanent tree shades (Wrigley, 1988; Pochet and Flémal, 2001; Seiman, 2003; DaMatta, 2004). Temporary shade is often planted as a shade for young coffee up to two years from planting in the field while permanent shade trees can be planted closely along inter-row lines which are thinned to leave normal shade pattern (Clifford, 1985; Ortiz *et al.*, 1989). Herzog (1994) pointed out the multipurpose nature of shade trees in coffee such as firewood, local constructions, traditional medicines and edible fruits. Napoles, *et al.*, (1990) studied the effect of shade or sun on arabica coffee seedlings on plant height, stem diameter, root length and number of leaf pairs when the plants were 7 months old. They found best results with seedlings grown under shade. Jaramillo and Gomez (1989) compared the microclimates of the arabica coffee grown under shade and in full sun and concluded that it is more advantageous to grow coffee under shade than in full sun. Shading of plantations of mature coffee trees suppresses the undesirable undergrowth thus helping in the control of weeds as well (Williams and Chew, 1979). Sun-grown coffee soils experience greater run-off and nutrient leaching and remain productive for only one-third to one-half compared with shaded plantations (Perfecto et al. 1996). But it is important to note that in case of a dense shade, like thick forests, coffee harvest is extremely very low and that growing coffee without shade is beneficiary where there are very good growing condition such as sufficient rain fall and abundant nutrient resource in case of the managed coffees (Pochet and Flémal, 2001). The advantage of shade for coffee growth include regulation of air temperature and maintenance of air humidity, increased soil moisture due to increased drainage (reduced run off), source of litter and organic matter, maintenance of good soil structure, enrichment of soil nutrients by bringing nutrients up from deep sub soil, reduction of over bearing thus reducing die-back of coffee plant, good fruit quality and chemical composition (Webster and Wilson, 1980; Guyot *et al.*, 1996; Reinhold, 2001). Beer *et al* (1997) and Holmgren (2000) also showed positive effects of shading plants mainly under dry conditions. There are some drawbacks of shade trees which include reduction of light intensity, competition for nutrients and water in dry seasons and for oxygen in wet season, alternate hosts for pests and disease in some shade trees and the shade trees may cause damage to the coffee plants when they fell down (Webster and Wilson, 1980; Beer *et al.*, 1997). Yacob Edjamo *et al.*, (1995) pointed out that coffee growth and dry matters considerably decrease despite the increased moisture content of the soil for coffee plantations grown in deep shade. According to Kimemia (1988), shade decreases yield potential because shade influences light intensity, leaf and soil temperature and rate of transpiration, growth, pest and diseases and weed growth. Shade trees filter and absorb the visible wavelengths used in photosynthesis; therefore an uneven shade is more essential than a uniform and dense shade (Kimemia, 1988). It is important to select and use shade trees preferentially since trees differ in their competitiveness with coffee plants as indicated by Nichols (1990). Carvajal, (1984) and Ramalho *et al.*, (1999) showed that the acclimation of *Coffea arabica* to high irradiance was nitrogen dependent and suggested that the application of adequate amount of nitrogen could be helpful in growing arabica coffee in open sun. It is obvious that the advantage of growing coffee in shade overweighs its disadvantages as sun-grown coffees require very high and uneconomical inputs for maintenance and other agronomical practices that are not affordable especially for the smallholders (Seiman, 2003).

1.5 Water deficit studies in coffee

Water deficit arises from low soil moisture and high transpiration rate and this has significant effects on the physiological functions of plants that result from the alteration of biochemical processes (Etherington, 1975 and Kramer, 1983). Plant responses to water deficits is revealed at all developmental stages of the plants which could determine the survival and fitness of the plant species (Hanson and Hitz, 1991). The regulation of photosynthetic activities was essential adaptation enabling plant species to avoid photodamage during exposure to drought, low temperature and other kinds of stresses (Toivonen and Vidaver, 1988; Lawlor, 1993; Eastman *et al.*, 1995; Fernandez, *et al*, 1997; Qui and Fry, 1997, and Jun, *et al.*, 2001).

Drought is considered as the main environmental stress greatly affecting coffee populations in different coffee growing countries (DaMatta, 2004; Miller and Conko, 2004). In Ethiopia, the recurrent drought is becoming the main threat to the coffee gene pool (together with other human impacts). Several literatures are available concerning coffee water relations. Some of these are: the work of Carr (2001) on irrigation requirements, effect of water potential on growth parameters conducted by Barros *et al.*, (1997) and effect of soil moisture on carbon isotope and gas exchange by Meinzer *el al.*, (1993). The effect of water deficits on flower opening was also demonstrated by Crisosto *et al.*, (1992). Drought tolerance in coffee has also been explored by many authors, so-far limited to nursery or glass house experiments as reviewed by DaMatta (2004). It has been mentioned that the arabica coffee exists in the wild state only in Ethiopia. Wild species have been considered potential sources for different traits like drought resistance more than cultivated (domesticated) species. But still, literature concerning ecophysiological responses of the wild arabica coffee to water deficits in case of Ethiopia is not available. This could mostly be because of the fact that there was surplus water available for coffee growth for the past several years which is now becoming a problem. Now days, the need for conserving the coffee gene pool in the wild state is increasing from time to time. This requires detailed *in situ* study on the physiological responses of coffee populations to water deficits in their natural ecosystems. Therefore, this study is an *in situ* experiment aimed at finding out some resistant land races/ accessions of *C. arabica* to water stress in the natural forest ecosystems.

2. OBJECTIVES

2.1 General objectives

1. To find out some physiological variations among arabica coffee populations along climatic gradients.

2. To investigate adaptability to water deficit in arabica coffee accessions.

2.2 Specific objectives

1. To investigate diurnal patterns of chlorophyll fluorescence and leaf water potential in coffee accessions.

2. To relate soil moisture levels and plant water potential values in different coffee accessions.

3.To relate variation in leaf water potential values, chlorophyll fluorescence and soil moisture at different seasons.

3. MATERIALS AND METHODS

3.1 Species description

Coffee plant is a dicotyledonous shrubby tree that belongs to the family *Rubiacea* of the genus *Coffea.* There are over 100 species of coffee but the main economically significant species are *C. arabica, C. liberica* and *C. canephora* (Purseglove, 1974b; Opeké, 1992; Faziolo *et al.*, 2000; Ruas *et al.*, 2000; Damatta, 2004). Coffee tree grows up to a height of 5 m (Cobley, 1976) but arabica coffee can grow as high as 8-10 m in the wild state with long and flexible branches and *C.canephora* (*robusta*) can grow even taller (Pochet and Flémal, 2001). Coffee trees tend to attain greater height in deep shades than in light shade with different canopy structures (Wrigly, 1988).

All coffee species exhibit the characteristics of C_3 plants and are diploid with 22 chromosomes except the arabica coffee that is the only tetraploid species with 22 (2n= 44) pairs of chromosomes (Wilson, 1987; Robinson, 1996). The central stem, called orthotropic stem, grows vertically upward and gives rise to the horizontal stem called plagiotropic stem (Purseglove, 1974b; Cobley, 1976; Tewalde- Berhan Gebregzabiher, 1978; Cambrony, 1992). It was described that the orthotropic stem produces two buds in the leaf axis whereby the upper bud gives rise to a pair of primaries (plagiotropic) whereas the lower bud remains dormant, which in case of damage of the main stem, produces suckers which replace the orthotropic stem (Wrigly, 1988).

The plagiotropic stem can further branch into secondary or some times into tertiary stems. The lower most primaries die back and remain intact for no any replacement, as the tree gets older and older (Purseglove, 1992). In arabica coffee, each new growth is distinguishable by the green epidermis of both orthotropic and plagiotropic stems as a result of new growth added to the current growth season and the amount of new current growth is proportional to the number of berries (Teweld-Berhan Gebiregzabiher, 1974). Lopez *et al* (1990) experimentally showed that a 4 years old tree could attain a height of 219.6 cm, a crown diameter of 129.7, an internode length of 5.2 cm and a berry production of 6.62 t/ha.

The leaves are simple opposite with short petioles. They are dark green in color and elliptical in shape. Interpetiolar stipules are always present. There are small cavities called domatia in the lower surface of the leaves (bulging out on to the super surface in arabica coffee). The leaves have a crossed pattern orientation on the trunks and suckers, while they lie on the same plane on the primaries (Pochet and Flémal, 2001).

Flowers sprout from a series of lateral buds in the leaf axils. Flowers are initiated right after the crop harvest but they are soon arrested and remain dormant until stimulated by a temperature shock and supply of one set of water (Cobley, 1976; Pochet and Flémal, 2001). Flowers open simultaneously after one set of rain (Purseglove, 1974b). Vickery (1974) observed that coffee plantation suddenly burst into bloom a week later after heavy rain (after few weeks of drought season) while continuously irrigated coffee did not bloom at all. The flowers are in aggregate (inflorescence) and are white in color with a pleasant odor. The floral parts are pentamorous (parts in five 5); united sepals; 5 petals with corolla tube; 5 stamens inserted in the corolla tube;

long anthers on slender upright filaments; pistils with inferior ovary containing 2 ovules and a short style with 2 short pointed stigma (Cobley, 1976; Cambrony, 1992; Pochet and Flémal, 2001). The fruits are drupe berries (cherries with two seeds /coffee beans) and have 3 distinctive portions: exocarp (pericarp), mesocarp and endocarp (parchment) in which the beans are found covered by the silver skin (Rothfos, 1980; Kochhar, 1981; Wrigly, 1988; Cambrony, 1992; Woiciechowski *et al.*, 2000).

The root system contains three parts: i) the taproot (the main root) which is used mainly for anchorage and the absorption of water, ii) the coaxial which branch from the tap root and grow vertically and used mainly for absorption of water and iii) the laterals which are also branches of the tap root and horizontally spread in the richest upper soil layer and are mainly used for the absorption of water (Cambrony, 1992; Casté, 1992). Coffee root growth is highly affected by many environmental factors which include soil texture and composition, soil aeration, drainage, water and mineral resources (Costé, 1992).

3.2 Study sites description

The study was conducted at sites where coffee grows in the wild as constituent of the forest These are the montane rainforests found in the South, Southwest and South Eastern parts of Ethiopia. Where conditions are suitable for its growth, coffee is also found as garden coffee, plantation coffee, forest and semi forest coffee (Figs.1 and 2). Forest coffee is self grown (natural) and found in the natural forests where it is originated and diversified. This is found in the south and southwestern parts of the country and it accounts for about 10% of the country's coffee (Tadesse, et al., 2002; STCP, 2004).

Semi-forest coffee is found in the south and southwestern parts of the country. This is also natural coffee like the forest coffee but in this case, the farmers own the forests for coffee farms. The farmers select the forest trees for appropriate shade by thinning them. They also slash the weeds every year to allow maximum crop harvest from the coffee trees. These semi-forests account for about 35 % of the total coffee production in the country. The garden coffees grow in the farmers' residences and are common mainly in the southern and eastern parts of the country. Garden coffees are planted at lower densities and they account for about 35% of the total coffee in the country. The plantation coffees are grown on plantations by the state and smallholder coffee farmers. The state owned coffees account for about 5% whereas the smallholders owned account for about 15% (Tadesse, et al., 2002; STCP, 2004).

Forest coffee Semi-forest coffee

Garden coffee Plantation coffee

Fig. 1. The four coffee production systems in Ethiopia (Source: STCP, 2004)

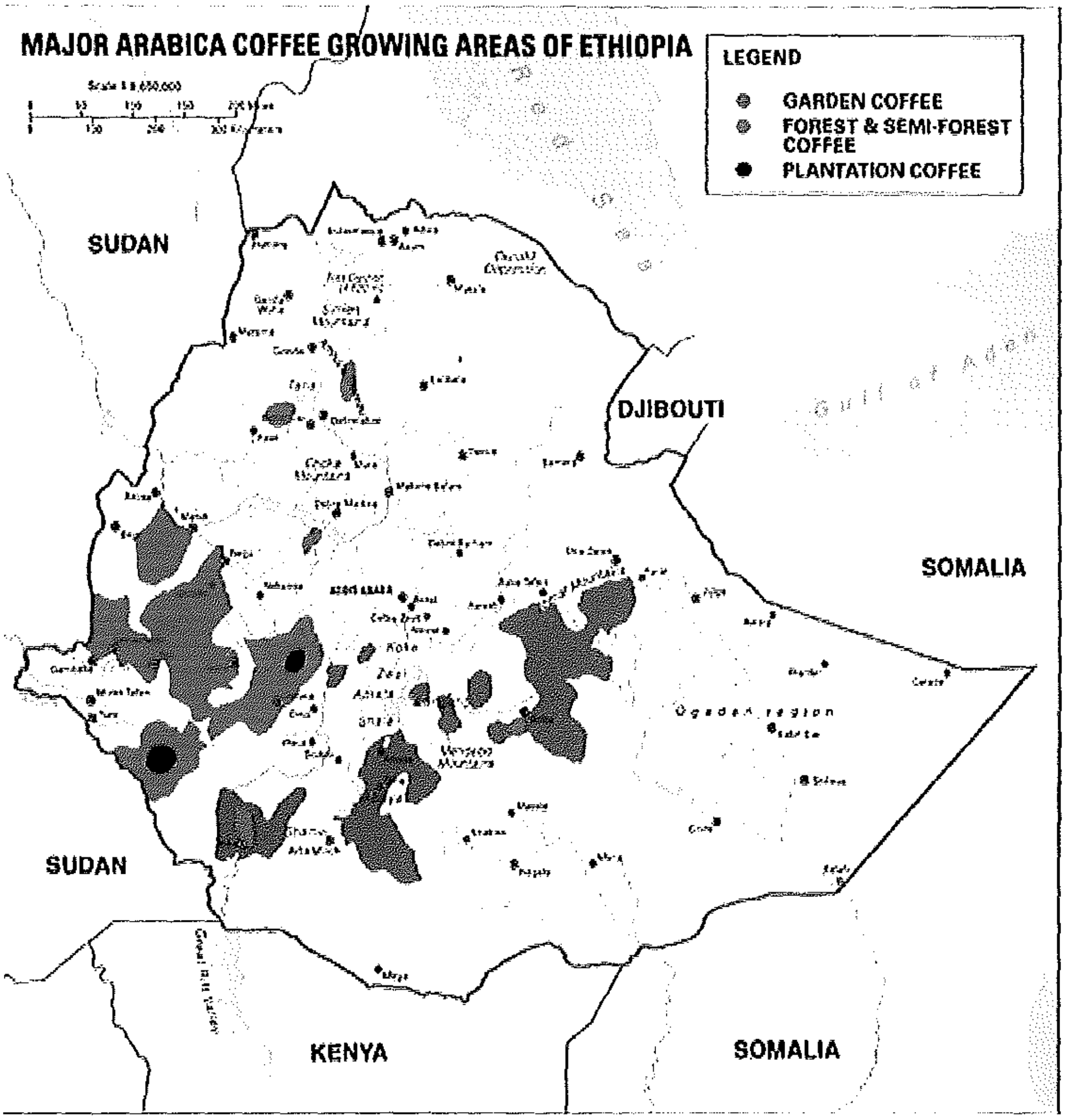


Fig. 2. Arabica coffee growing regions in Ethiopia (Source: Coffee and Tea Authority)

Four major sites were selected from August 11-22, 2003. These are: Harena forest, Bonga forest, Sheko and Yayu forests. Part of the Harena Forest selected for the study is found in Dolo Mena (Southwestern region). Dolo Mena is a District in Bale Zone of Oromia Regional State found at 575 km from Addis Ababa, at 40^0S and 5^0E. The mean annual temperature is about 22.6 ^{0}C, ranging from mean minimum of 16.2^{0}C to maximum of 29 ^{0}C (Fig. 3).

Bonga Forest is found in Bonga (Southern region), a district found in Kefa Zone of South Nations, Nationalities and People's Administrative Region at 446 km from Addis Ababa, at 36^0S and 5^0W. The mean annual temperature is about 19 ^{0}C, ranging from mean minimum of 11.5 ^{0}C to maximum of 26.4 ^{0}C (Fig. 4).

Sheko Forest is found in Sheko (Southern region, at 20 km west of Mizan Teferi), a District in the Bench- Maji Zone of the South Nations, Nationalities and People's Administrative Region at 589 km from Addis Ababa, at 35^0S and 5^0W. The mean annual temperature is about 21.4 ^{0}c, ranging from mean minimum of 15.5^{0}C to maximum of 27.4^{0}C (Fig. 5).

Yayu Forest is found in Metu Zone (Southwestern region) of Oromia Regional state at 562 km from Addis Ababa, at 36^0S and between $8^0$and 9^0W. The mean annual temperature is about 20 ^{0} C, ranging from mean minimum of 12.1 ^{0}C to maximum of 26.1 ^{0}C (Fig. 6). Each of the four sites is divided into three sub sites (which are about 5-30 km apart) arbitrarily named as sub site 1, sub site 2 and sub site 3. Table 1 shows the location of all of the sub sites. The Southeastern region has a bimodal rainy season whereas the South and Southwestern regions have a monomodal type. Figures 3- 6 show the Clima diagrams (Walter, 1985) all the sites.

Table 1. The location of the 12 sub sites

Site	Sub site	Local name	Latitude (°)	Longitude (°)
1.DoloMena (Bale)	1	Manget	6. 48	39. 75
	2	_	6. 48	39.75
	3	_	6. 49	39. 74
2.Bonga	1	Konba	7. 31	36. 05
	2	Arabacasha	7. 28	36.21
	3	Alemgono	7. 30	36. 06
3.Sheko	1	Beko 1	7. 11	35. 43
	2	Beko 2	7. 12	35.43
	3	Shimi	7. 07	35. 42
4.Yayu	1	_	8.39	35. 79
	2	_	8. 39	35. 79
	3	_	8.39	35. 79

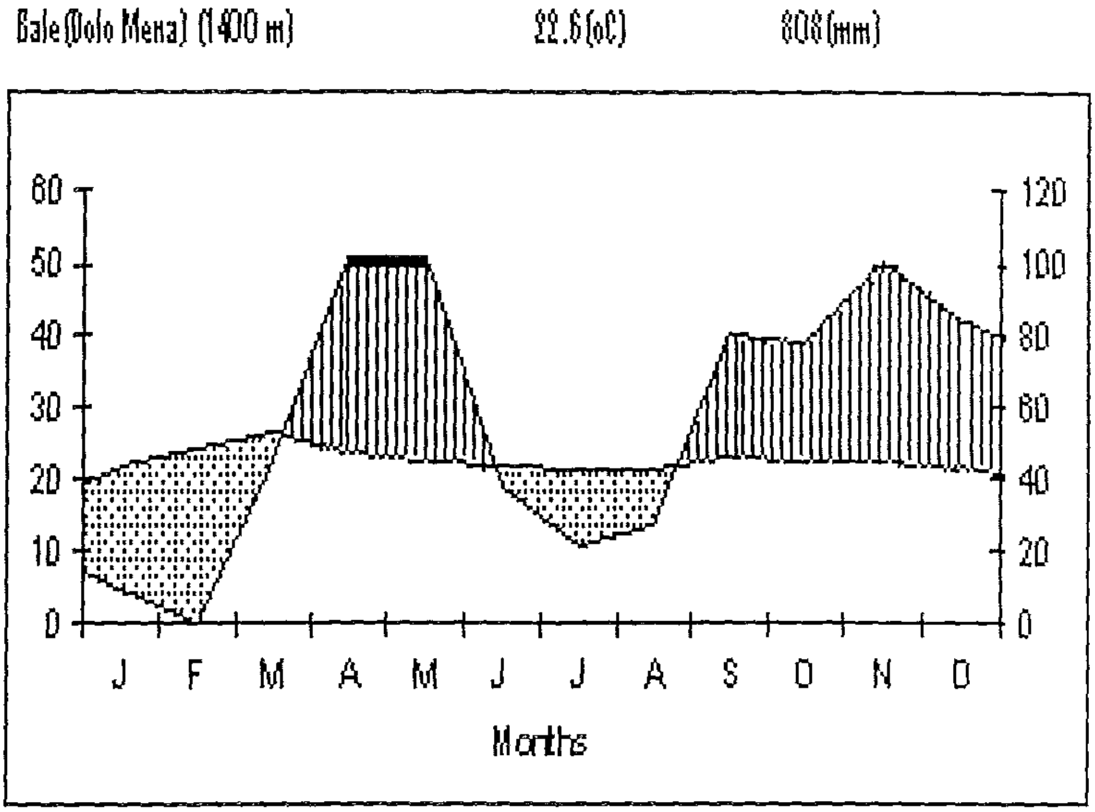
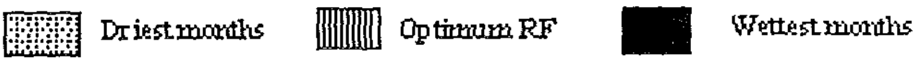


Fig. 3. Clima diagram of Bale (Data source: National Metrological Services):



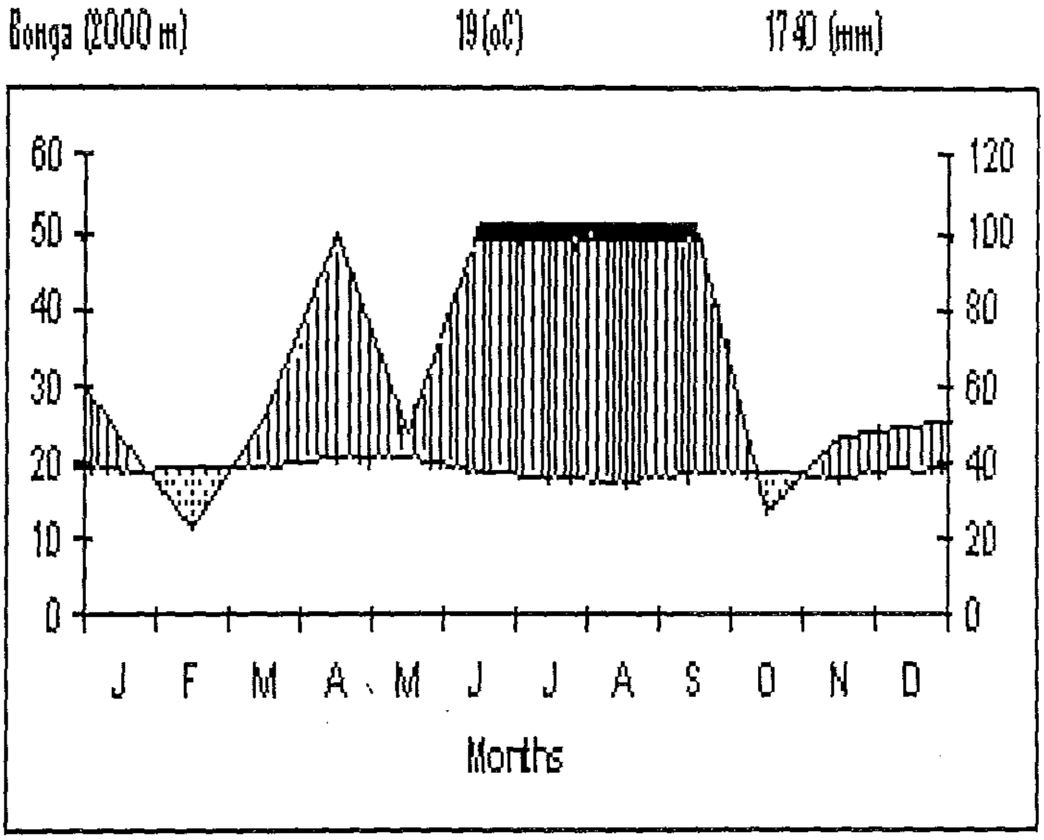


Fig. 4. Clima diagram of Bonga (Data source: National Metrological Services):

Driest months — Optimum RF — Wettest months

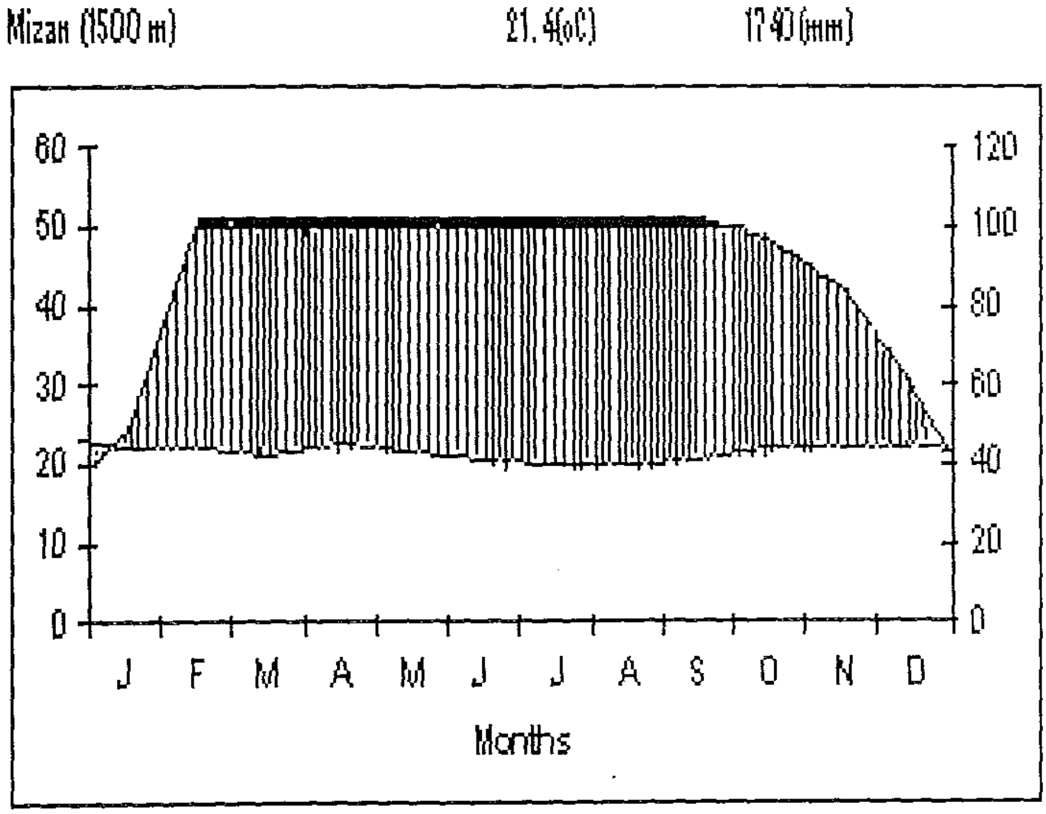
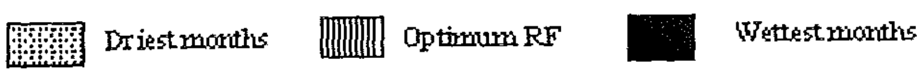


Fig. 5. Clima Diagram of Mizan (Data source: National Metrological Service):



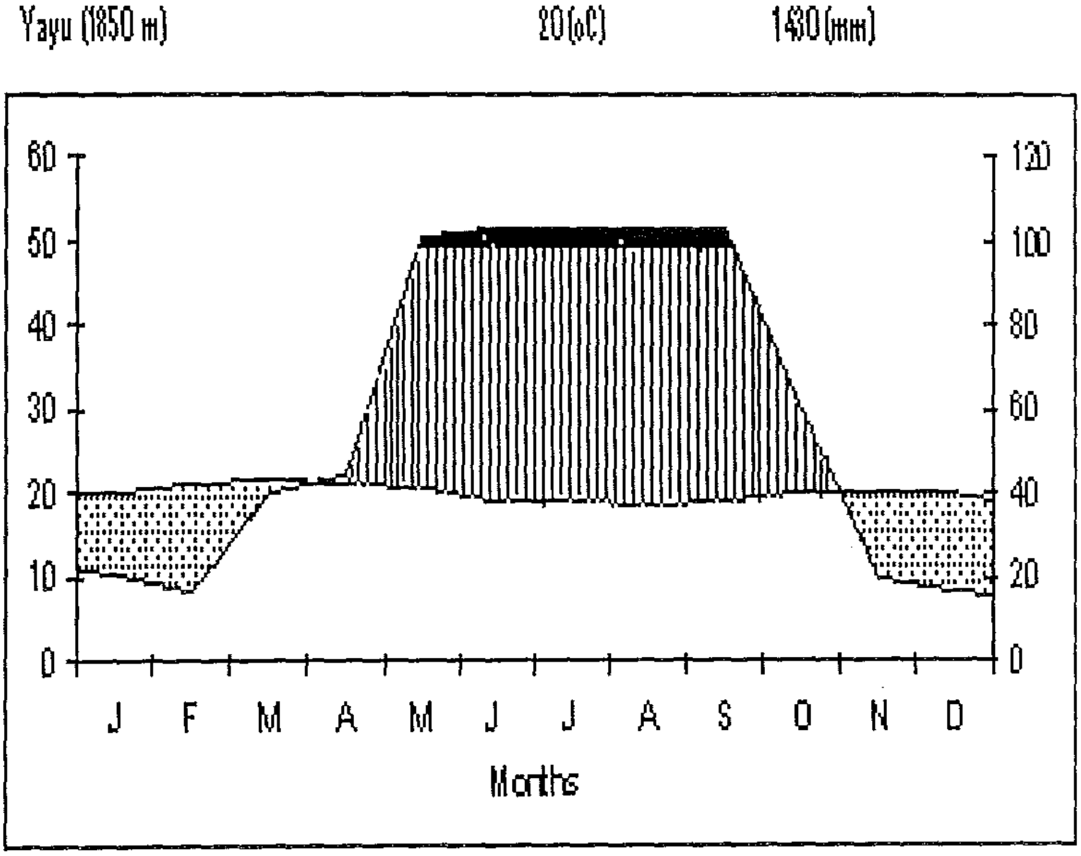


Fig. 6. Clima diagram of Yayu (Data source: National Metrological Services):

Driest months   Optimum RF   Wettest months

3.3 Soil Moisture Content

The volumetric soil moisture content was measured by a portable soil moisture meter (Type HH2 Delta T Devices Ltd. 128, Low Road, Bruwell, Cambridge, CB5. OEJ, UK). Measurements were conducted in both wet and dry seasons. In the wet season, records were taken at distance of 0.50 m and 1 m from each of twelve coffee trees in all the sub sites and the values were compared. But in the dry season daily course records were taken for soil samples at 0.50 m and 1 m from each of three coffee trees. In four of the sub sites (Bonga 1, Yayu 1, Yayu 2 and Yayu 3), soil moisture deeper than the length of the rods of the Theta Probe was also recoded. In this case, the probe was buried at a depth of 0.30 m and soil moisture was recorded at half- an-hour intervals without disturbing the probe. Soil moisture variation with respect to slope was also measured along slope gradient in Sheko sub sites.

3.4 Soil Water Potential

Soil water potential was measured by the portable soil sanction tensiometer (Quick draw tensoimeter, Eijikamp, Giesbeek, The Netherlands). In the wet season, measurement was conducted at a distance of 0.50 m at the depth of 0.15 m, 0.30 m and 0.45 m. But in the dry season measurements were conducted only at a depth of 0.20 m.

3.5 Leaf water potential

Leaf water potential was measured by the portable Plant Moisture Stress (PMS) instrument (Pump-Up pressure chamber, Covallis, Oregon USA). Hourly courses, predawn and midday leaf water potential measurements were taken. Healthy and fully-grown leaves at similar nods were used. All midday values below –21 bars could not be recorded because this was the minimum value that can be read from the gauge of the PMS (the PMS can measure values from 0 up to -21 bars only).

3.6 Slope

Slope was measured by the portable instrument (called Clinomaster, SILVA, CM-360%-M) at Sheko site. Measurement was conducted at 2 m intervals following the slope gradient in percentages.

3.7 Chlorophyll fluorescence

Chlorophyll fluorescence was measured by the Pulse Adapted Modulation (PAM) fluorometer (Junior PAM; Heinz Walz Gmbh.Eichenring 6.D-91090 Effeltrich. Germany). Coffee trees that are about 2 m tall and fairly in similar shade conditions and of the same age (4 to 6 years) were chosen. Three leaves were chosen form three positions in the canopy: lower, middle and upper canopies. The leaves were maintained in their natural orientation during the measurements not to disturb the amount of the radiation falling on the exposed surfaces. The comparison of chlorophyll fluorescence as influenced by the effect of shade was also measured in Bonga and Yayu sites. In the forests (Bonga and Yayu sites), two contrasting trees, one in deep shade condition and the other in full sun (obtained as the result of open canopies) for light hours of the day were identified for the measurement of chlorophyll parameters. In the forests it was a problem to get coffee trees that are in full sun for all of the light hours of the day. Therefore the study of the effect of shade in particular was restricted to the time when full sunshine was available for the sun trees to get a good contrast. The daily courses of effective quantum efficiency ((Fm′ -F)/Fm′ or ΔF/Fm′) as well as the minimal and maximal chlorophyll fluorescence yields (F and Fm′ respectively) were measured.

3.8 Analysis of Data

The data collected from the field measurements were analyzed using Pearson Correlation, descriptive statistics and one-way ANOVA using SPSS software. The soil moisture and chlorophyll fluorescence data collected by the instruments were downloaded to PC and then prepared in such a way that they could be analyzed using the software. In case of soil moisture, comparisons of the mean values of all the sites and sub sites, both in the wet and dry seasons were done using case summary reports, descriptive statistics and one-way ANOVA. For chlorophyll fluorescence data, the comparisons of the ΔF/Fm′, ETR, F, and Fm' was done using descriptive statistics and one-way ANOVA; case summary was used only for the daily course values. For SWP and LWP, descriptive statistics and case summary reports were used. The Pearson's correlation was used to evaluate the correlations between the ΔF/Fm' and LWP, ΔF/Fm' and soil moisture, LWP and soil moisture, SWP and soil moisture and between soil moisture and slope.

4. RESULTS

4.1 Soil water status

4.1.1 Volumetric soil moisture content

Significant difference was not seen between soil moisture measured at 0.50 m and 1 m distances from each coffee tree at P=0.05 (Fig. 7). Comparison of soil moisture in the wet and dry seasons is shown on Fig. 8 A. In Bale (Dolo Mena), the wet and dry seasons differ from the other sites because of the bimodal rainy season of the region. That is why minimum values are observed for this site on Fig. 7. Therefore, no rainy (wet) season was encountered during the two-round measurements, thus results for Bale were discussed as two dry seasons. In this site (Bale), higher soil moisture values were recorded in September than in January (Fig. 8B) in all of the subsites. The lowest soil moisture was found in Bale 1 whereas Bale 2 and Bale 3 were almost similar in September. In January, all the three sub sites (of Bale) had almost similar soil moisture distribution.

In the other sites, soil moisture varied from 46.4% (Bonga 1) to 50.2% (Bonga 2) during the wet season (Fig. 8 A). Almost similar soil moisture distribution was found in all the sites in the wet season. During the dry season, maximum and minimum mean soil moisture values were recorded in Bonga 3 (22.7%) and Sheko 3 (9. 9%), respectively. There was significant difference between the wet and dry seasons' soil moisture in all the sub sites. Maximum seasonal range was recorded in Sheko 3 (74%) and minimum in Sheko 1 (65%).

The diurnal soil moisture variation (surface layer) is shown on Fig. 9. In all cases, a slight increase was observed until 9:30, and then after, an intermittent decreasing and increasing trend was observed through out the measurements. Figure 10 shows soil moisture measured at a depth of 0.3 m at Bonga 1, Yayu 1, Yayu 2 and Yayu 3. At Bonga 1, it was 26% for the first three records and decreased to 25.9% for the next three records and farther decreased to 28.5% for the other three records and remained at 25.9% for the last four measurements. In Yayu 1, only two values were recorded. It was 18.4% for the first four records and remained at 18.3% for the rest of the measurements. In Yayu 2, it started with the initial value of 17.1% and reached a maximum value of 18.4% at about midday and slowly decreased until the end of the experiment. In Yayu 3, it remained at 17.6% throughout the course of the measurement. Figure 11 shows the correlation between soil moisture (% by volume) and slope (%) measured in Sheko (no data for the other sites). It shows a strong negative correlation.

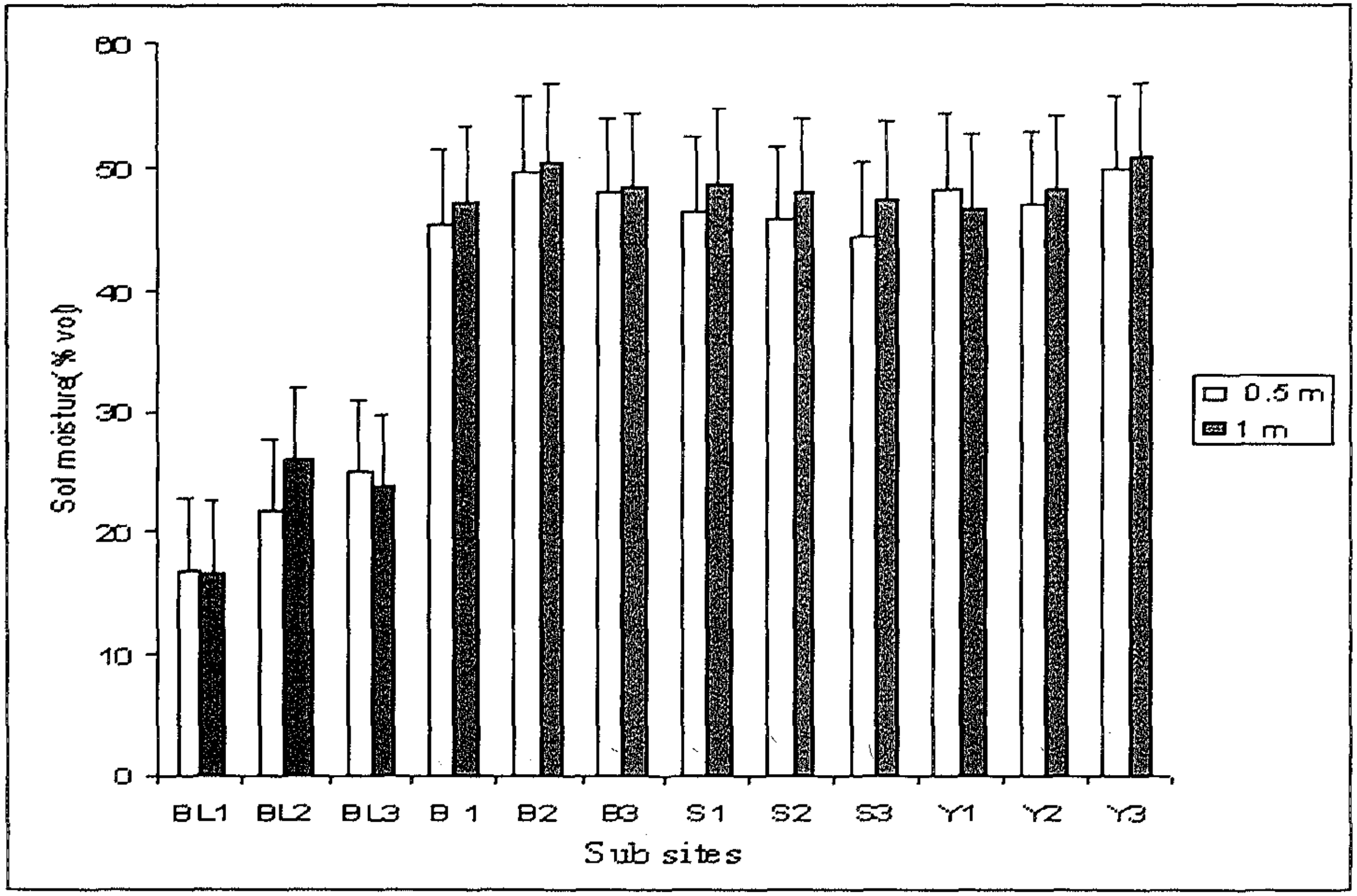
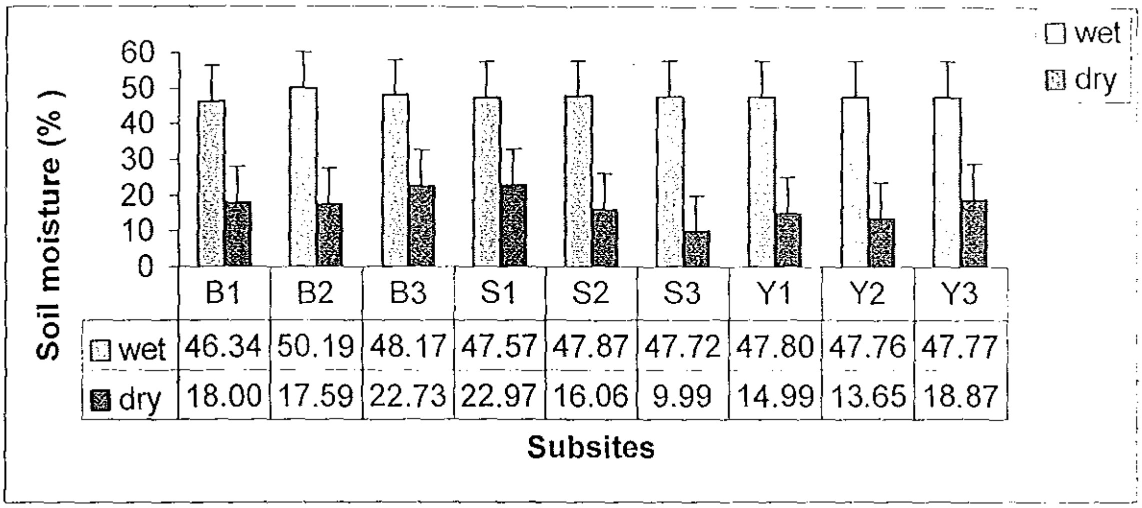
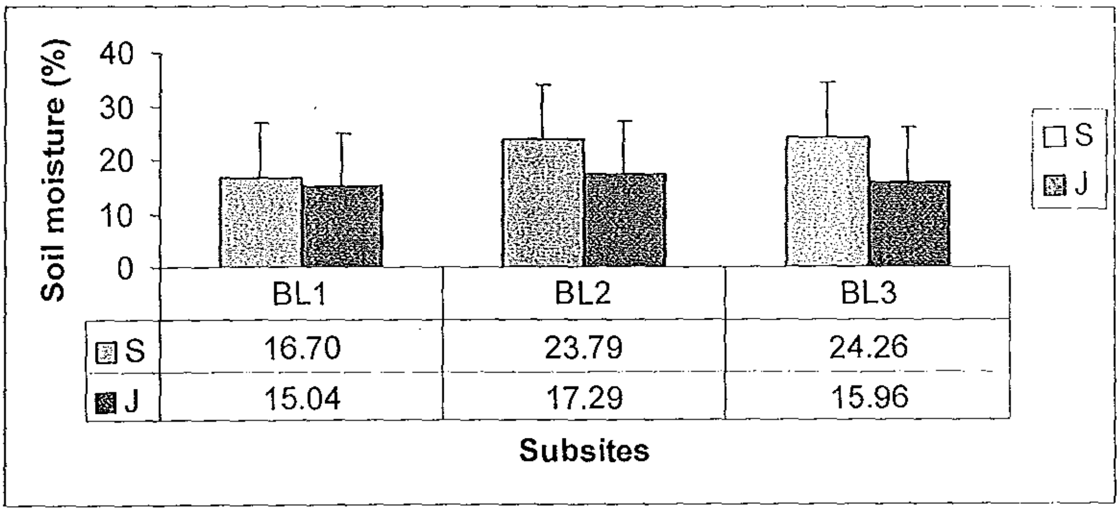


Fig 7. Bar chart showing soil moisture measured at 0.5 m and 1 m distances from individual coffee tree (BL1= Bale 1, BL2= Bale 2, BL3=Bale 3; B1=Bonga 1, B2 =Bonga 2, B3= Bonga3);S1=Sheko 1, S2= Sheko 2, 3=Sheko; Y1= Yayu 1, Y2= Yayu 2, Y3=Yayu 3).



A. Bonga, Sheko and Yayu



B. Bale(Dolo Mena)

Fig 8 . Comparison of wet and dry season soil moisture content (A): (B1=Bonga 1, B2 =Bonga 2, B3= Bonga 3; S1=Sheko 1, S2= Sheko 3; Y1= Yayu 1, Y2= Yayu 2, Y3=Yayu) 3 and two dry periods in Bale (B): (BL= Bale 1, BL2= Bale2, BL3=Bale 3); (S= September, January)

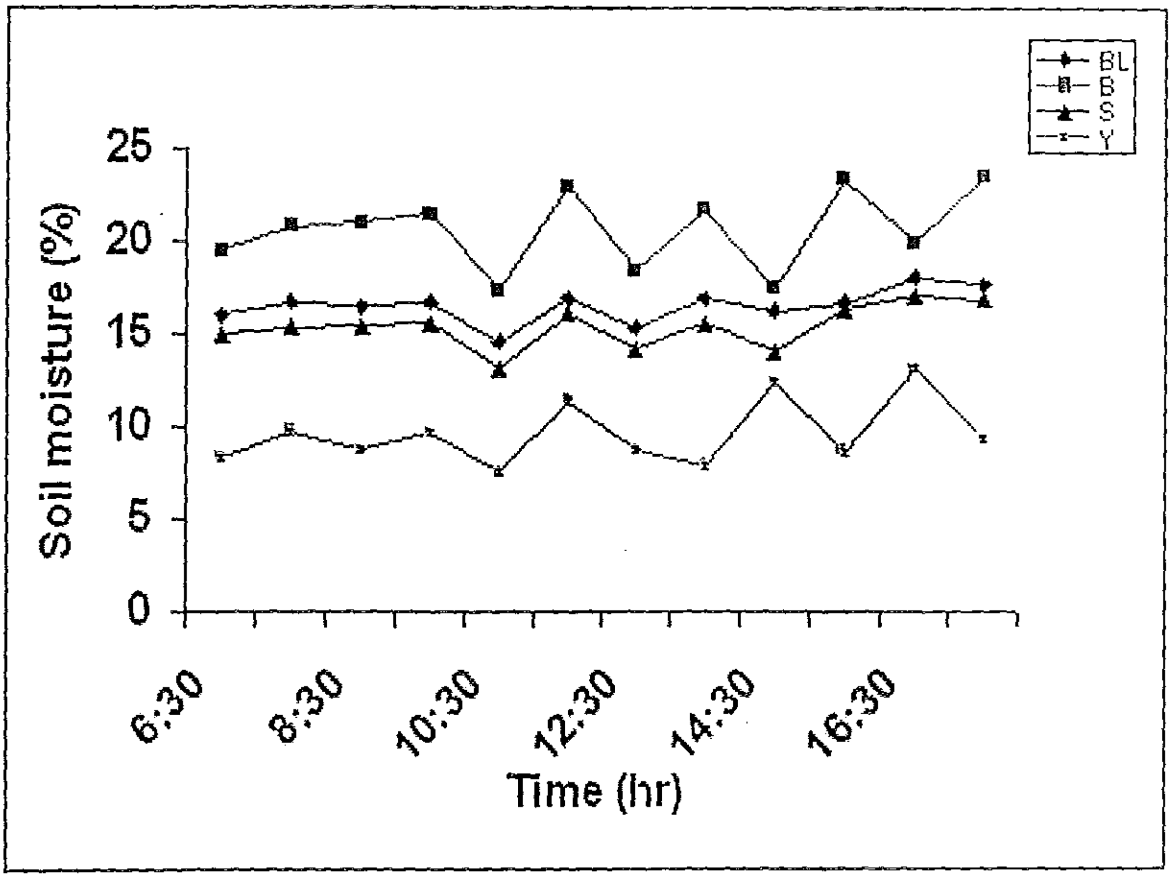


Fig 9. Diurnal soil moisture at the surface layer (BL=Bale, B=Bonga, S=Sheko, Y=Yayu)

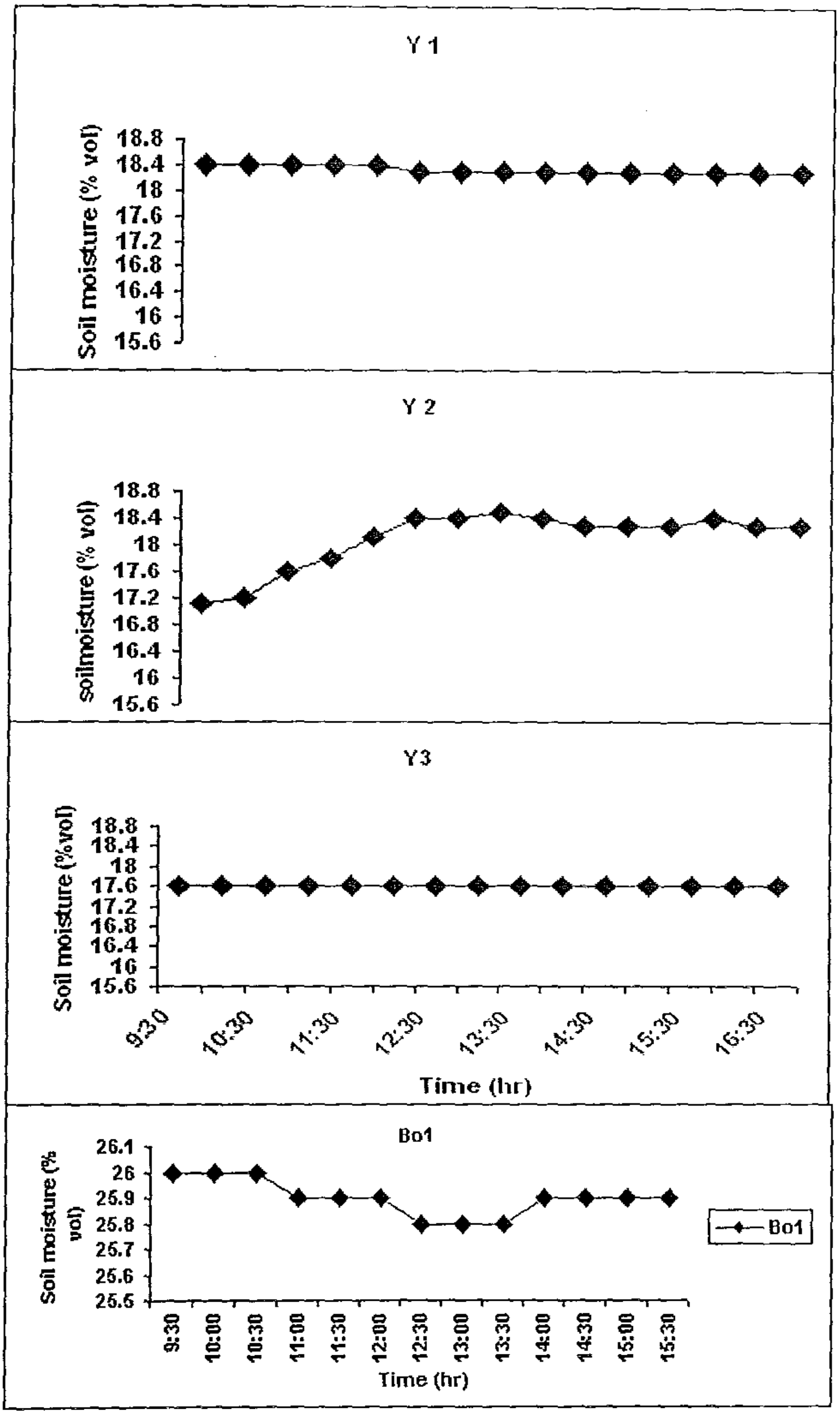


Fig 10. Diurnal Soil moisture at a depth of 0.30 m

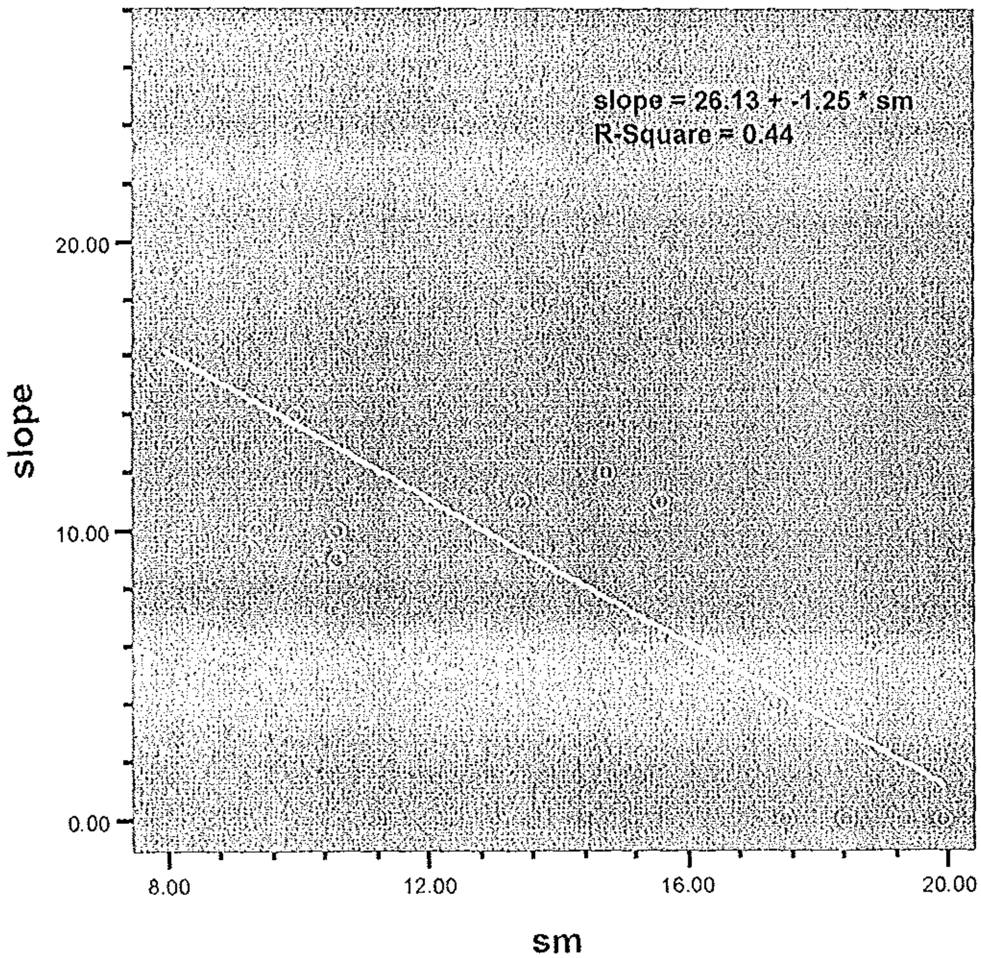


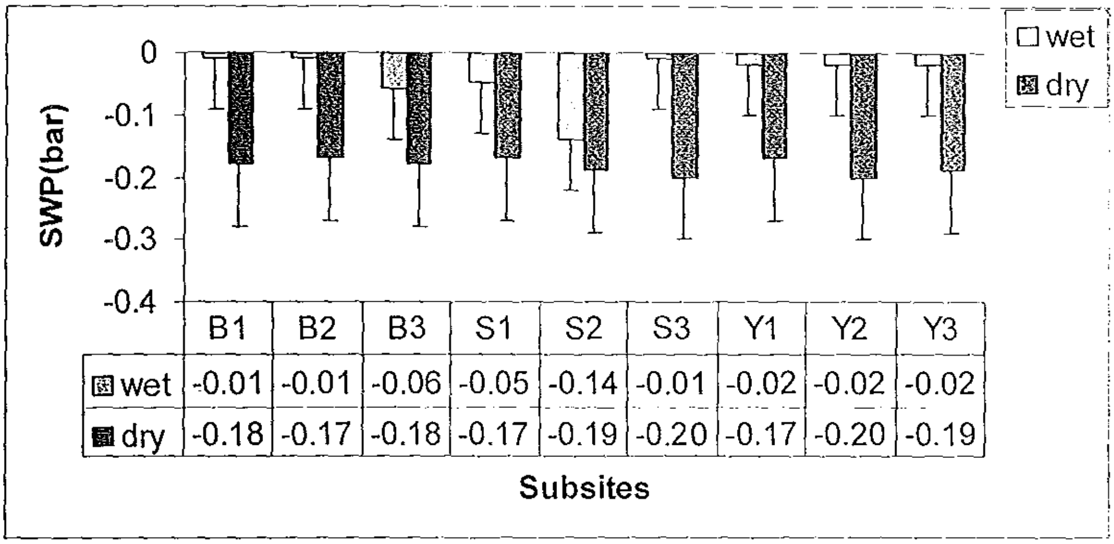
Fig 11. Correlation between soil moisture (sm) and slope

4.1.2 Soil water potential (SWP)

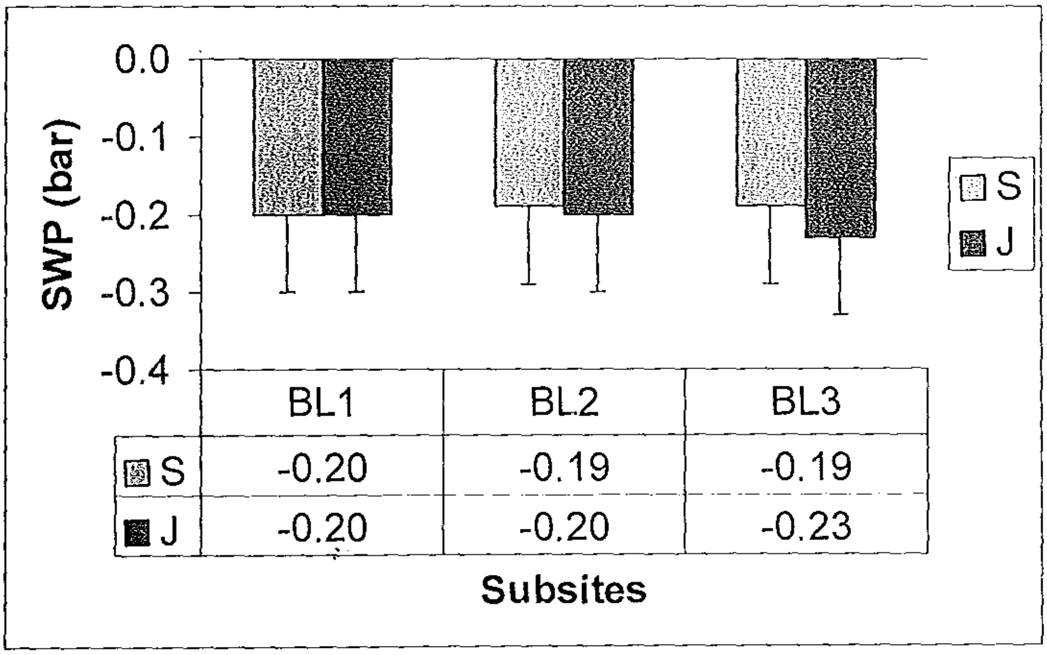
The SWP measured at the different depths in the wet season (at 0. 15 m, 0.30 m and 0.45 m) did not show significant difference at 0.05 level of significance. The mean values of all the subsites for the three depths were compared (Table 2) and the descriptive statistical analysis are shown (Appendix 3). Comparison of the wet and dry seasons' SWP is shown on Figure 12A. In the wet season, maximum values were recorded in Bonga 1, Bonga 2 and Sheko 3 and minimum values were recorded in Sheko 1, Sheko 2 and Bonga 3. In the dry season, minimum SWP was measured in Sheko2, Sheko 3, Yayu 2 and Yayu 3, whereas the remaining subsites had similar values. Comparison of the wet season's SWP does not include Bale since the particular time of measurement was actually dry season in this site. Similar SWP values were recorded in Bale subsites in both months except that slightly lower value was measured in Bale 3 in January (Fig. 12 B).

Table 2. Soil water potential (in bars) at three different depths: 0.15 m, 0.30 m and 0.45 m.

Sub site	Swp at 0.15 m (bar)	Swp at 0.30 m (bar)	Swp at 0.45 m (bar)
BL 1	-0.32	-0.32	-0.33
BL 2	-0.21	-0.20	-0.22
BL 3	-0.22	-0.23	-0.23
B 1	-0.10	-0.16	-0.13
B 2	-0.14	-0.15	-0.11
B 3	-0.06	-0.05	-0.06
S 1	-0.05	-0.03	-0.03
S 2	-0.14	-0.14	-0.18
S 3	-0.15	-0.15	-0.14
Y 1	-0.01	-0.01	-0.01
Y 2	-0.02	-0.02	-0.02
Y 3	-0.02	-0.02	-0.02



A. Bonga, Sheko and Yayu



B. Bale

Fig 12. Seasonal variation of soil water potential. (A): (B1=Bonga 1, B2 =Bonga 2, B3= Bonga 3), S1=Sheko 1, S2= Sheko 3, Y1= Yayu 1, Y2= Yayu 2, Y3=Yayu 3 and two dry periods in Bale (B): (BL= Bale 1, BL2= Bale 2, BL3=Bale 3).

4.2 Leaf water potential (LWP)

The diurnal LWP of all the sites is shown on Figure 13. In all the sites, relatively higher values were recorded at the beginning of the measurements and then a continuous decline was seen. Minimum values were reached between 13:00-14:00 h and recovery started from 14:00 h. The recovery was not the same for all the sites. The minimum value that could be read by the gauge was –21 bars. Therefore the midday values below –21 bars were not measured.

The graph of predawn and midday LWP is shown on Fig 14. A 45^{0} line bisecting the X- and Y-axes was used for interpretations of the values following Mitloenher (2000) and Kindeya Gebrehiowt (2003). In Bonga, both predawn and midday values were very high (the highest of all) while in Yayu, very low midday (but higher than Sheko) and high predawn (but lower than Bonga) were measured. In Bale, the midday values lie between Bonga and Yayu (lower than Bonga but higher than Yayu) but the predawn values were lower than Yayu. In Sheko, the midday values were higher than Yayu whereas most of the predawn values were the least of all. Comparison of the mean midday LWP values of the wet and dry seasons is shown on Figure 15, and as indicated, significant differences were found (P=0.05). In the wet season, maximum and minimum LWP values were measured in Yayu 3 (>-21) and Yayu 2, respectively. No significant variation was seen in the other subsites. In the dry season, maximum and minimum LWP values were measured in Bonga 2 and Sheko 3 (>-21 bar), respectively. In Bale1 and Bale 2, almost similar LWP values were recorded in the two measurement periods.

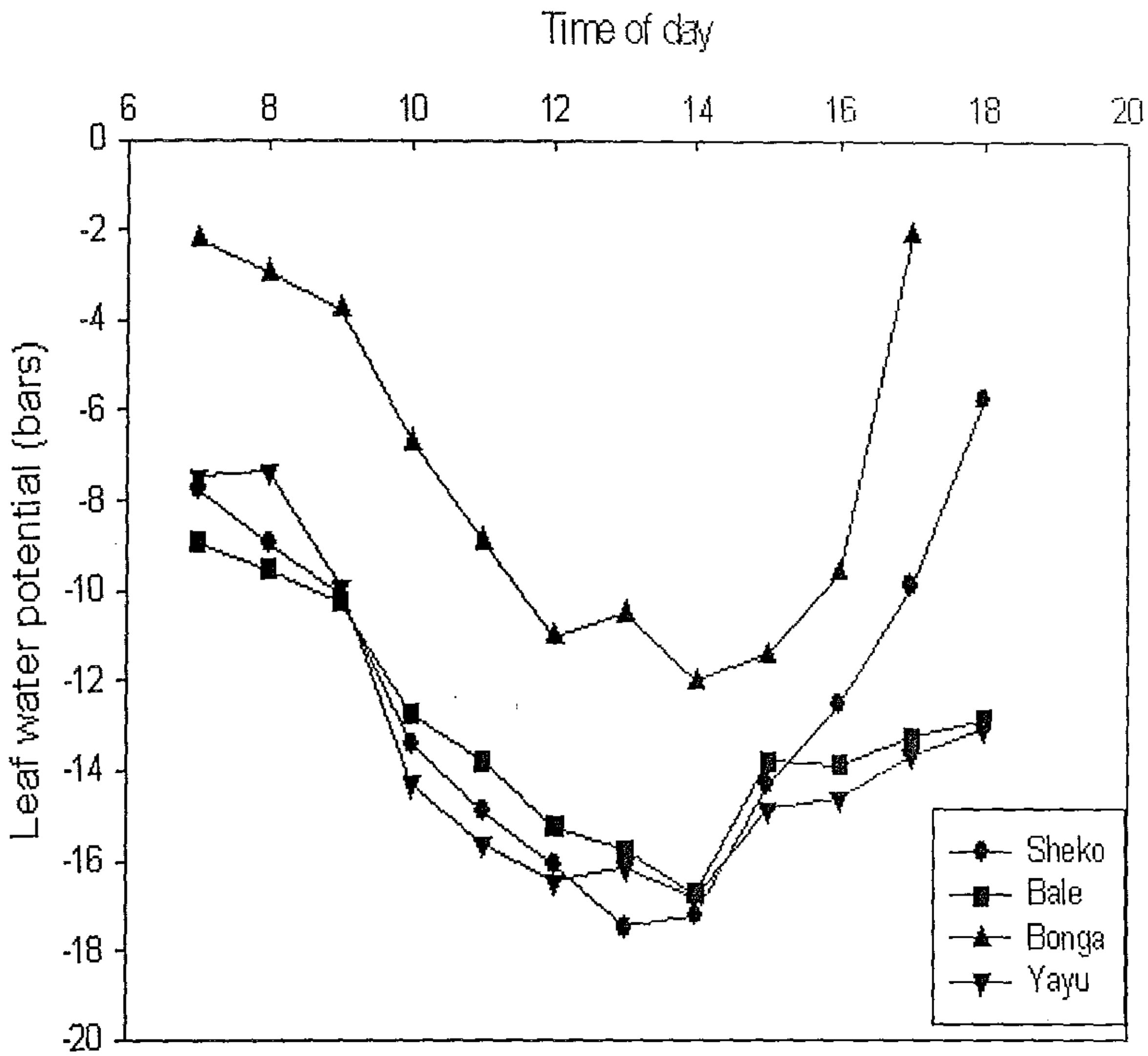


Fig 13. Diurnal leaf water potential for the 4 sites

Table 3. Predawn, midday and diurnal range leaf water potentials for the 4 sites

Site	Leaf water potential (bar)		
	Predawn	Midday	Range
Bale	-5.75 (a)	-14.62 (a)	8.87 (a)
Bonga	-2.66 (b)	-11.71 (b)	9.05 (b)
Sheko	-6.95 (c)	-17.60 (c)	10.65 (c)
Yayu	-3.10 (d)	-16.80 (d)	13.10 (d)

Note: Values followed by different letters in each column are statistically different (P=0.01)

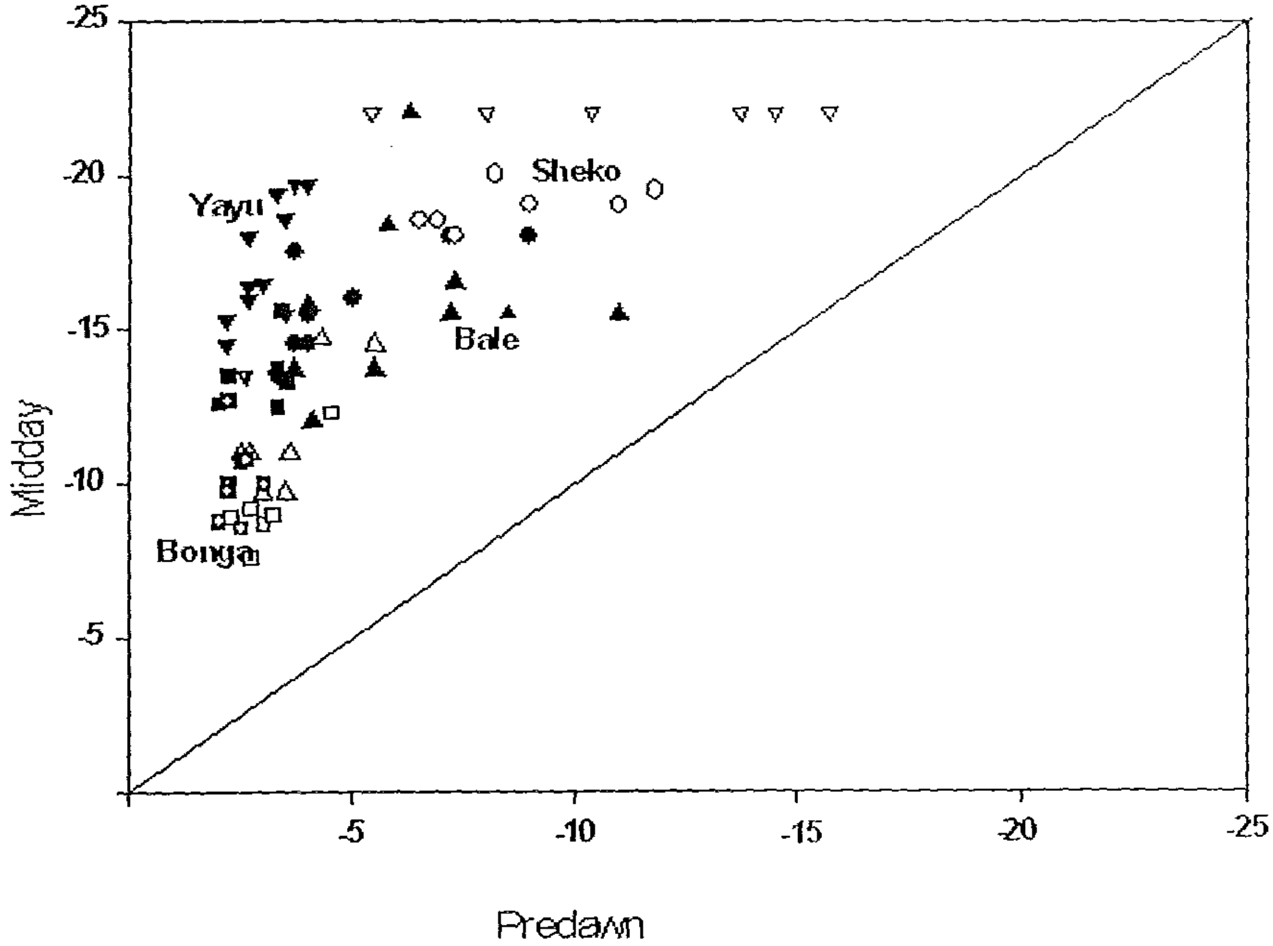
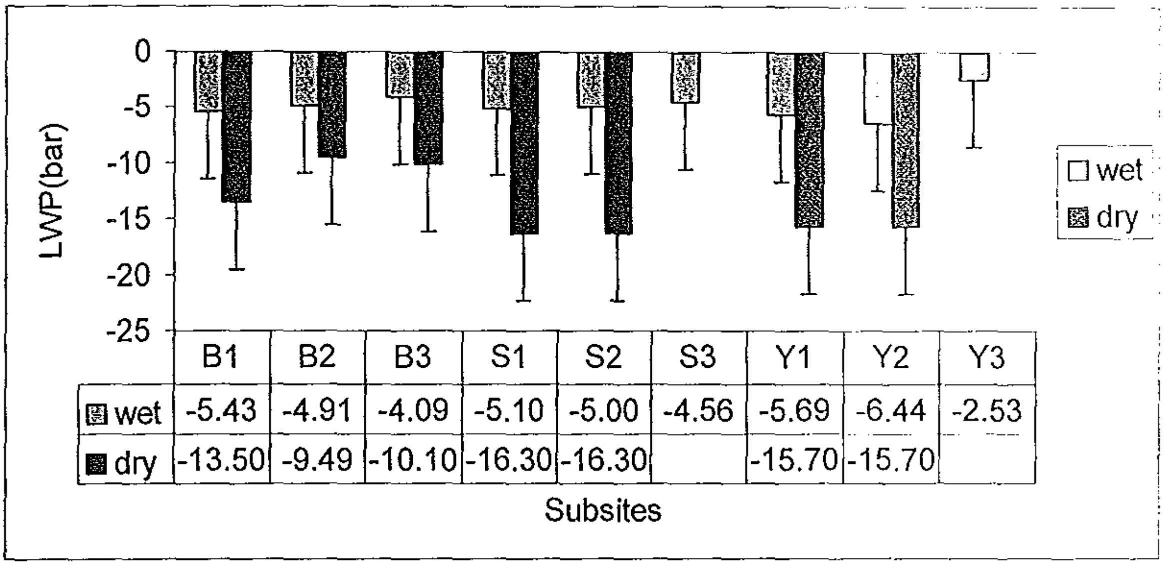
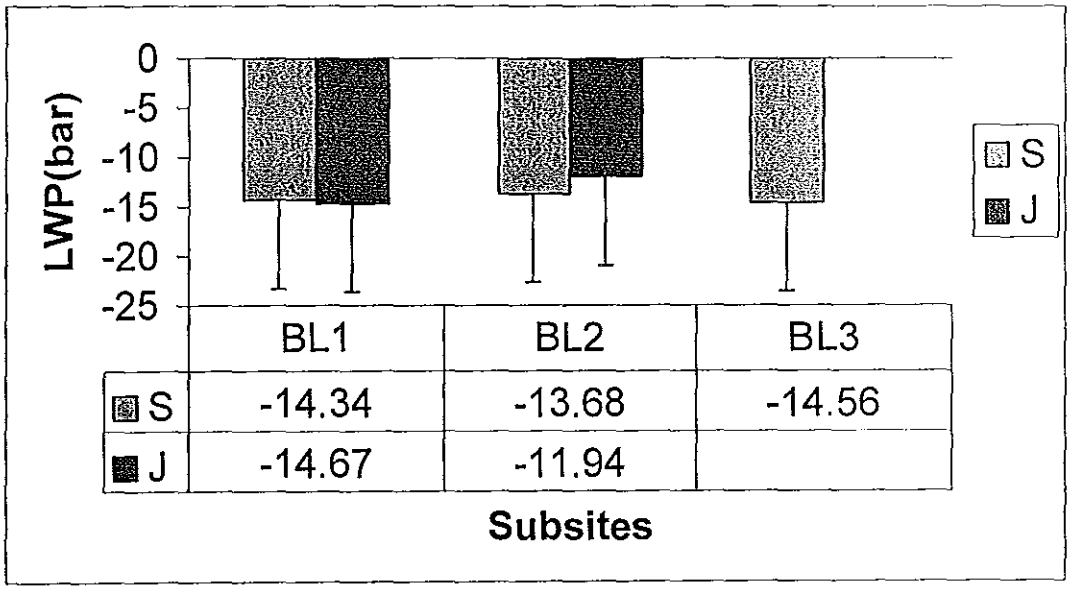


Fig 14. Midday and Predawn LWP (bar): (▲=Bale 1, △ =Bale 2; ■=Bonga 1, □=Bonga 2, ◘=Bonga 3; ●=Sheko 1, O= Sheko 2; ▼=Yayu 1, ▽=Yayu 2).



A. Bonga, Sheko and Yayu



B. Bale

Fig 15. Comparison of midday leaf water potentials in different seasons (A): (B1=Bonga 1, B2 =Bonga 2, B3= Bonga 3), S1=Sheko 1, S2= Sheko 3, Y1= Yayu 1, Y2= Yayu 2, Y3=Yayu 3 and two dry periods in Bale (B): (BL= Bale 1, BL2= Bale 2, BL3=Bale 3); (S= September, January)

4.3 Chlorophyll fluorescence

The graph of diurnal chlorophyll fluorescence yield ($\Delta F/Fm'$) of the older, medium aged and younger leaves is shown on Figure 16. Comparison of the fluorescence yield did not show significant difference among the three age groups of leaves. In all cases, fluorescence yield decreased starting from the predawn higher values and maximum depression was reached at midday and recovery was started after that and continued until the end of the experiment (in the evening). The maximum fluorescence yield measured at the predawn was lower than the value of unstressed plant leaves, which is 0.83.

The mean values of the medium leaves were used to compare the diurnal chlorophyll fluorescence yield of all subsites. Bale1, Bonga1, Sheko1, Sheko 2, Sheko 3 and Yayu 3 had relatively higher values whereas there was no significant difference among the other subsites (Fig. 17 and Table 3 and 4). Table 4 shows comparison of chlorophyll fluorescence yield of the sites based on the means of subsites. Slightly higher values were recorded in Bale and Yayu whereas Bonga and Sheko had lower values.

The light response curves for Bonga and Yayu sites are shown on Fig. 18. The fluorescence yield as well as relative electron transport rate (ETR) was lower in Bonga 3 whereas Bonga 1 and Bonga 2 were almost similar. Yayu 3 showed maximum values of both parameters from the Yayu site. Fluorescence yield decreased for all values of the photosynthetically active radiation (PAR) whereas the ETR increased continuously up to around 552μ $m^{-2}s^{-}1$ value of PAR and then decreased in all the sub sites.

Comparison of the wet and dry seasons' photosynthetic performance among coffee accessions in Bonga and Yayu is shown on Figure 19. The dry season's fluorescence yield was greater than that of the wet season in Bonga 1, Bonga 2 and Yayu 1. The wet season photosynthetic performance was greater than the dry season at lower values of PAR in Yayu 2 and Bonga 3 but almost equal at higher values of PAR whereas in Yayu 3 there was no significant variation at lower values of PAR but at higher values, the dry season's photosynthetic performance was greater than the wet season's performance. Comparison of the mean values of all the sites showed that the dry season's fluorescence yield was greater than that of the wet season (see Appendix 1).

Comparison of sun and shade tree photosynthetic performance in Bale and Yayu coffee accessions is shown on Figure 20. As can be seen from the graph, the fluorescence yield of shade coffee trees was greater than that of the sun coffees.

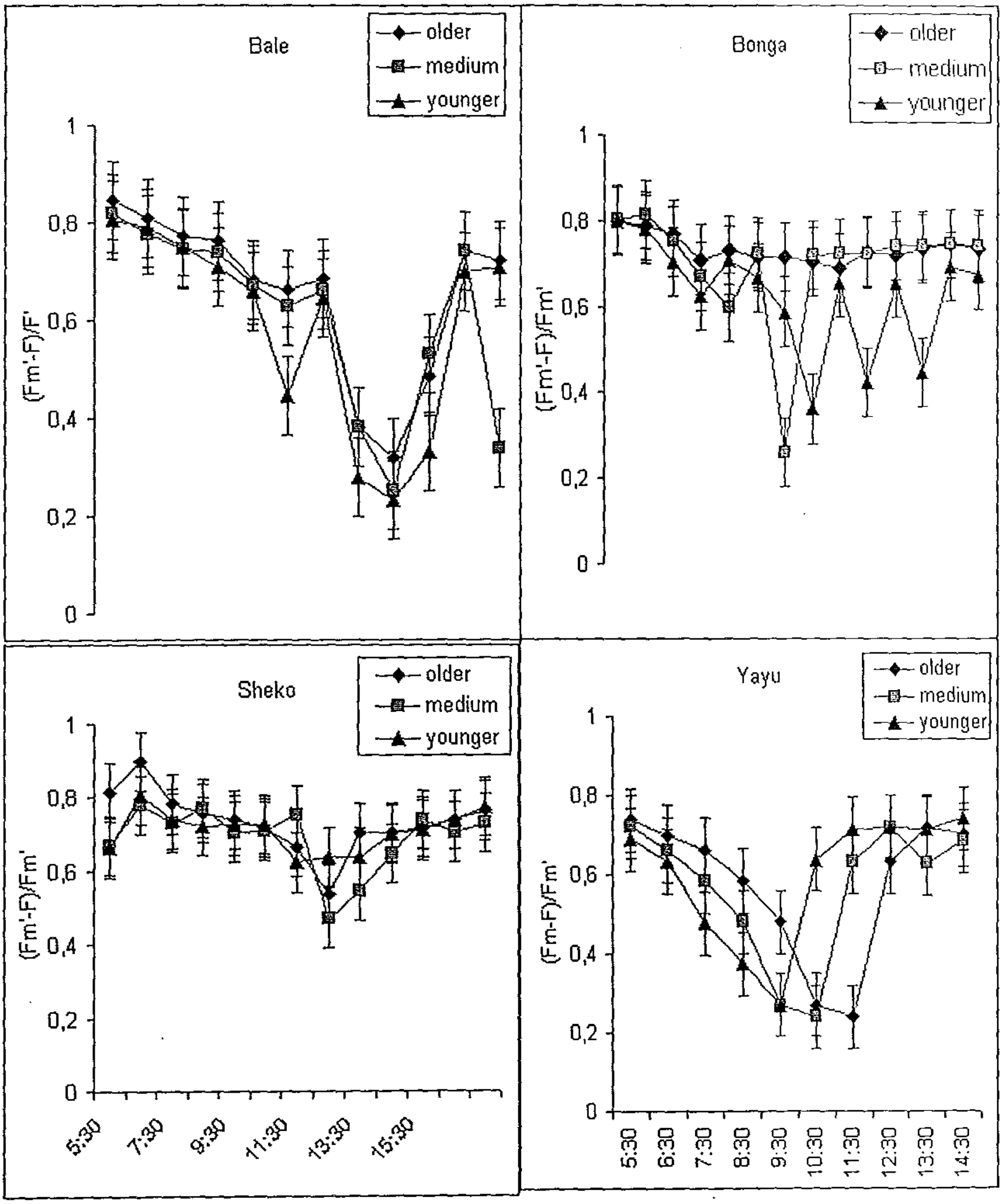


Fig 16. Comparison of diurnal chlorophyll fluorescence yield of older, medium and younger coffee leaves

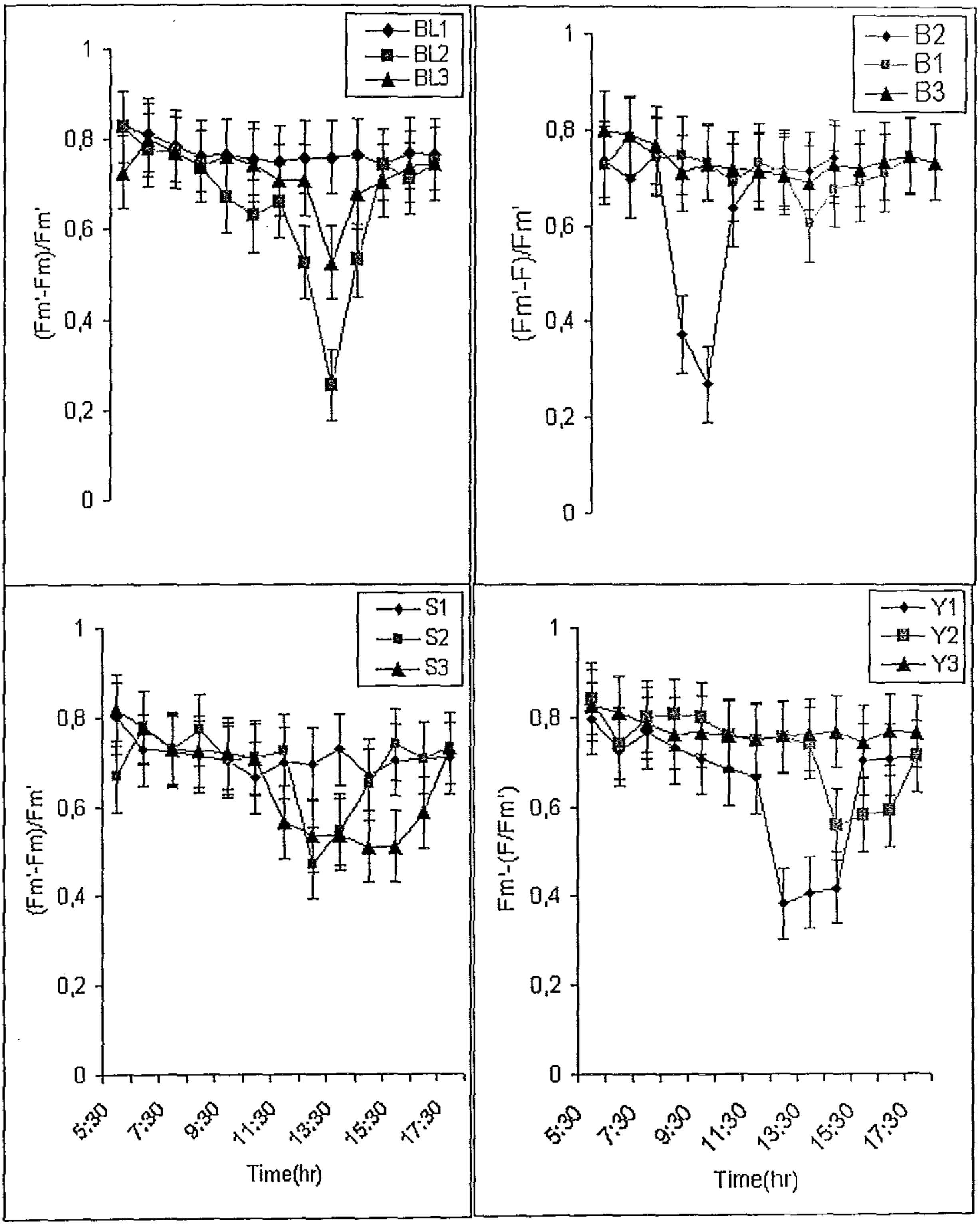


Fig 17. Comparison of diurnal chlorophyll fluorescence yield in all subsites (BL= Bale 1, BL2= Bale 2, BL3=Bale 3; B1=Bonga 1, B2=Bonga 2, B3=Bonga 3; S1=Sheko 1, S2=Sheko3; Y1= Yayu 1, Y2= Yayu 2, Y3=Yayu 3)

Table 4. Comparison of the mean values of diurnal chlorophyll fluorescence yield (ΔF/Fm') of all the sites (P=0.05)

(Bale) Dolo Mena	ΔF/Fm'	Bonga	ΔF/Fm'	Sheko	ΔF/Fm'	Yayu	ΔF/Fm'
1	0.77±0.01	1	0.71±0.01	1	0.72±0.01	1	0.66±0.02
2	0.62±0.30	2	0.70±0.03	2	0.71±0.01	2	0.69±0.02
3	0.71±0.02	3	0.69±0.01	3	0.69±0.01	3	0.77±0.01

Table 5. Comparison of the mean values of diurnal chlorophyll fluorescence yield (ΔF/Fm'), minimal (F) and maximal (Fm') fluorescence of all the sites (P=0.05).

Site	ΔF/Fm'	F	Fm'
(Bale) Dolo Mena	0.71±0.01	147.50±12.46	508.13
Bonga	0.70±0.01	472.63±19.64	1544.09
Sheko	0.66±0.01	262.76±13.45	767.50
Yayu	0.72±0.01	218.68±12.46	780.46

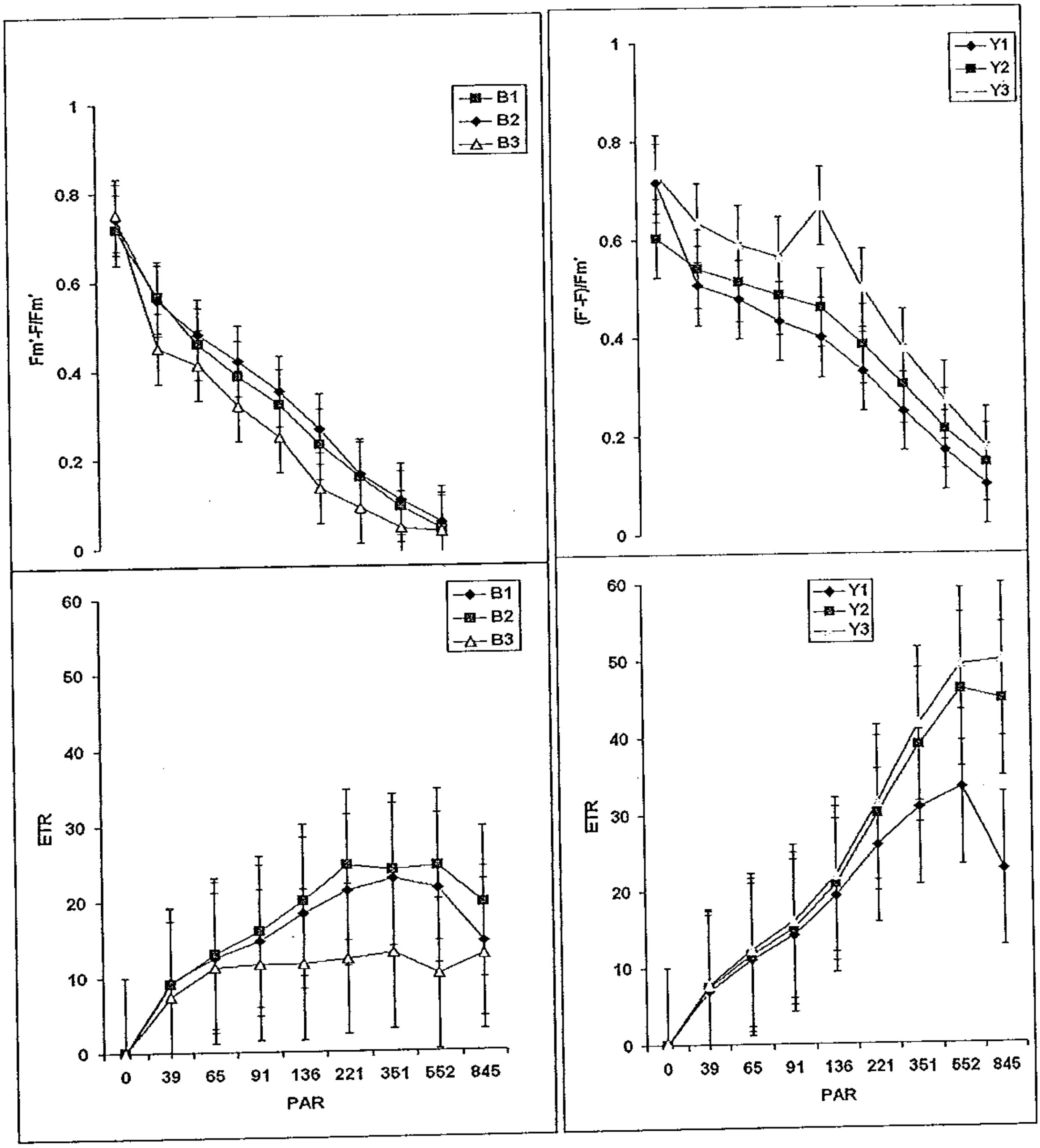


Fig 18. Light response curve showing chlorophyll fluorescence yield (ΔF/Fm') and electron transport rate (ETR) of coffee accessions in Bonga and Yayu sites (B1=Bonga 1, B2= Bonga 2, B3= Bonga 3,Y1= Yayu 1, Y2=Yayu 2, Y3= Yayu 3)

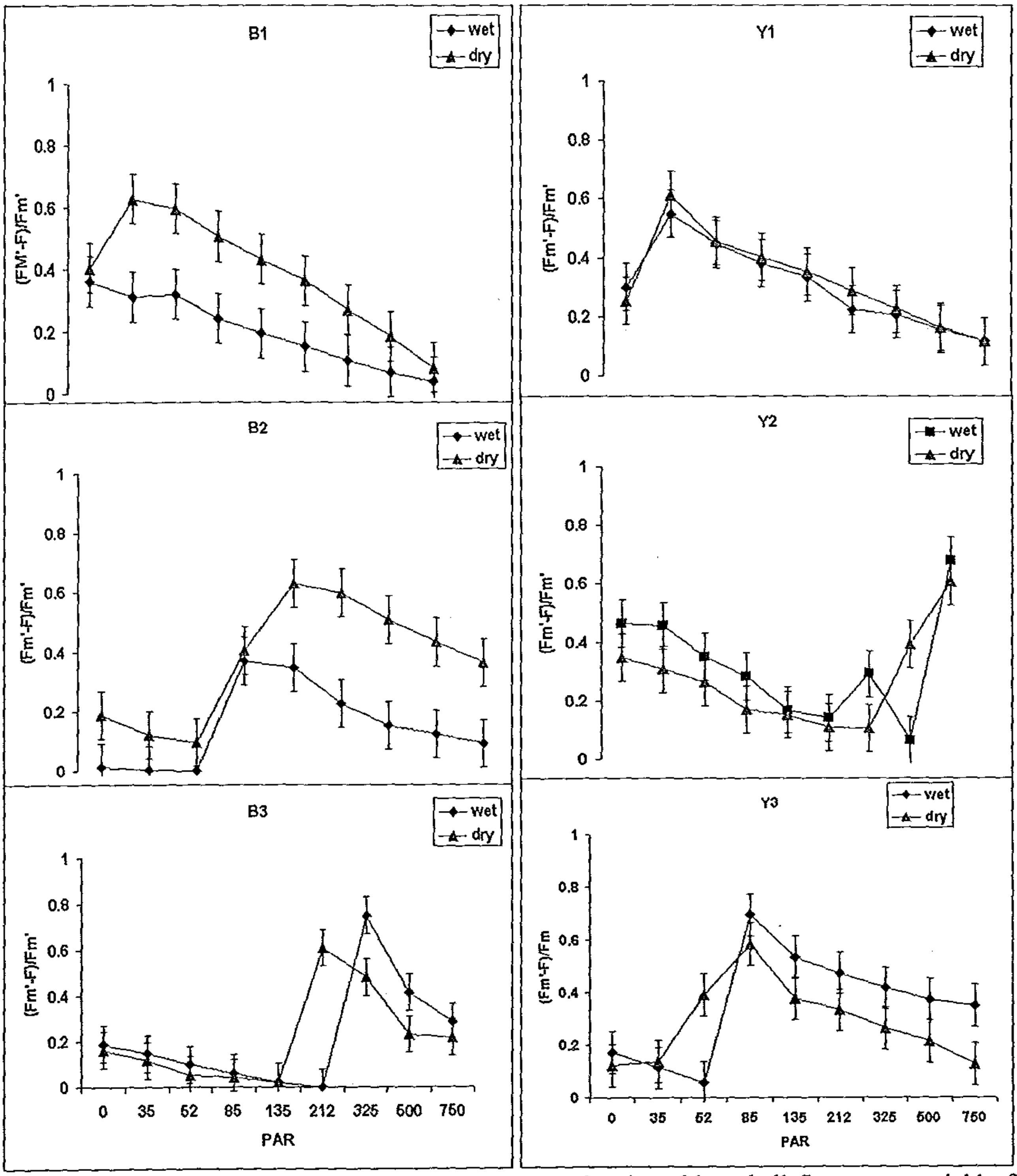


Fig. 19. Wet and dry seasons Light response curve showing chlorophyll fluorescence yield of coffee accessions in Bonga and Yayu (B1= Bonga 1, B2= Bonga 2, B3= Bonga 3, Y1= Yayu 1, Y2= Yayu 2, Y3= Yayu 3)

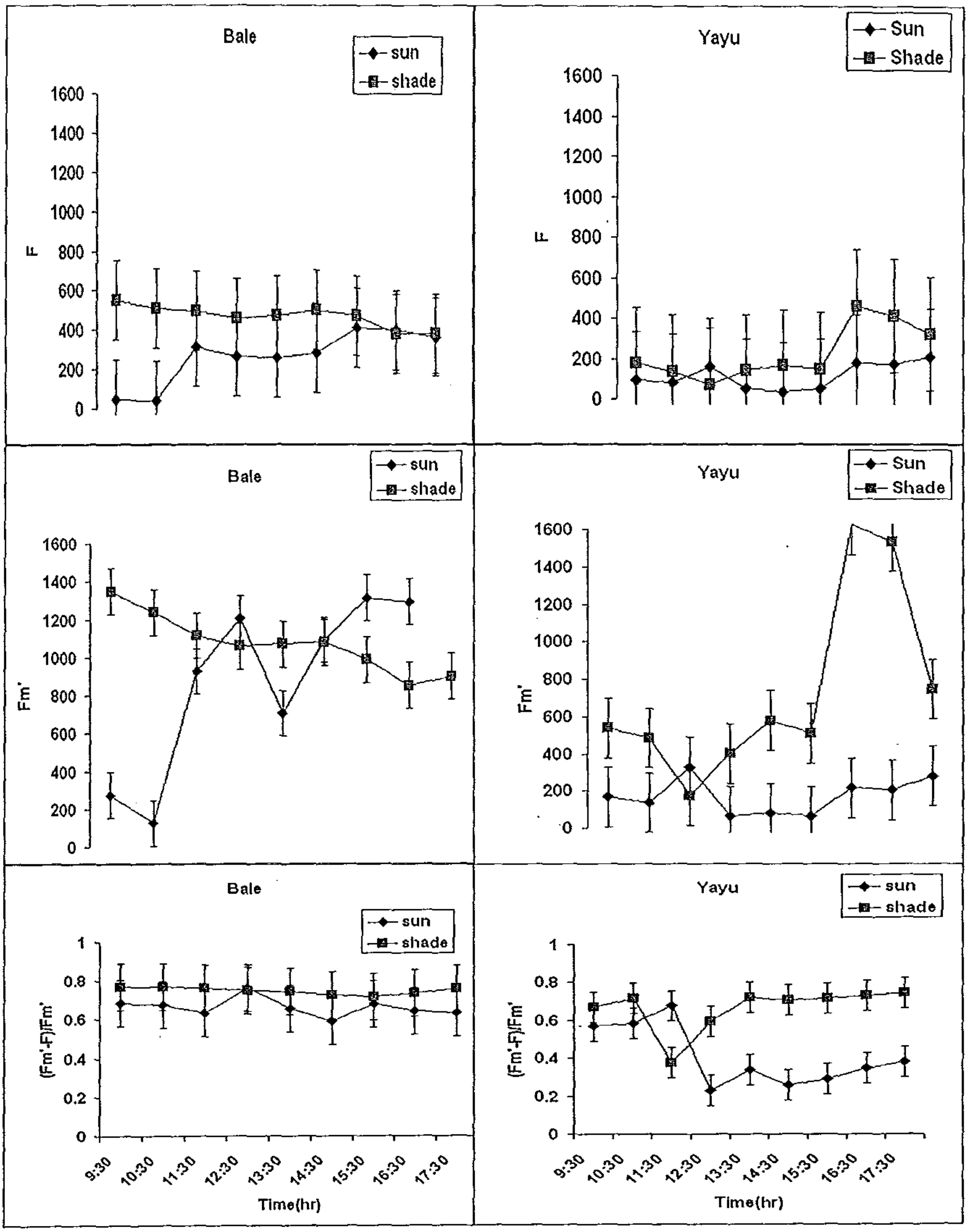


Fig. 20. Photosynthetic performance of coffees in full sun and shade

4.4 Correlations: Chlorophyll fluorescence, leaf water potential, soil moisture content, soil water potential.

The fluorescence yield and leaf water potential were weakly but positively correlated as shown on Figure 21. The fluorescence yield was also weakly (and positively) correlated to soil moisture; Figure 22 shows these correlations based on the mean values. A relatively stronger correlation was found between leaf water potential and soil moisture (Fig. 23), but the strongest correlation was found between soil moisture and soil water potential as shown on Figure 24. The correlations between all the parameters were in the following order: soil moisture versus soil water potential (47%) > soil moisture versus leaf water potential (10%) > leaf water potential versus effective quantum yield (2%) > effective quantum yield versus soil moisture (1%).

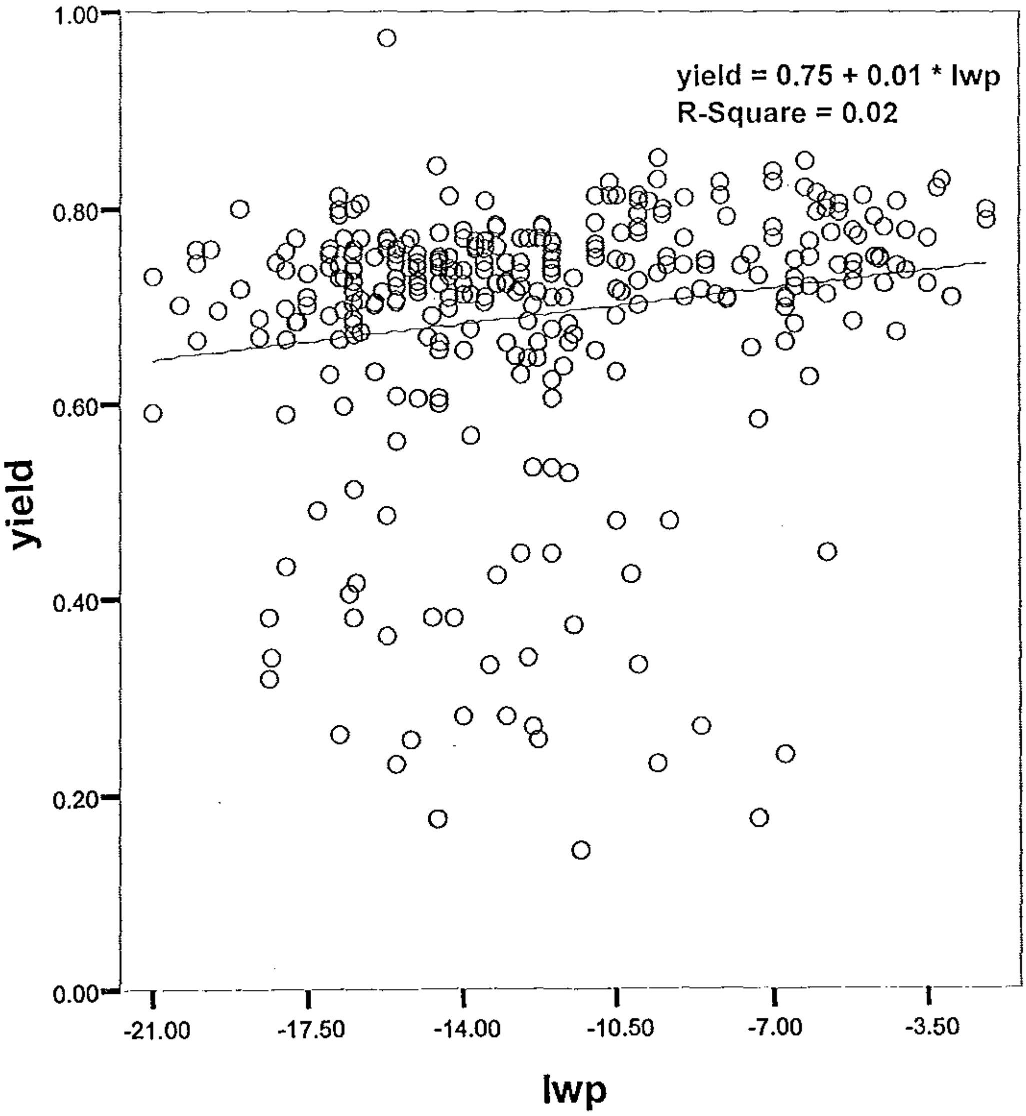


Fig. 21. Correlation between yield (fluorescence yield) and leaf water potential (LWP)

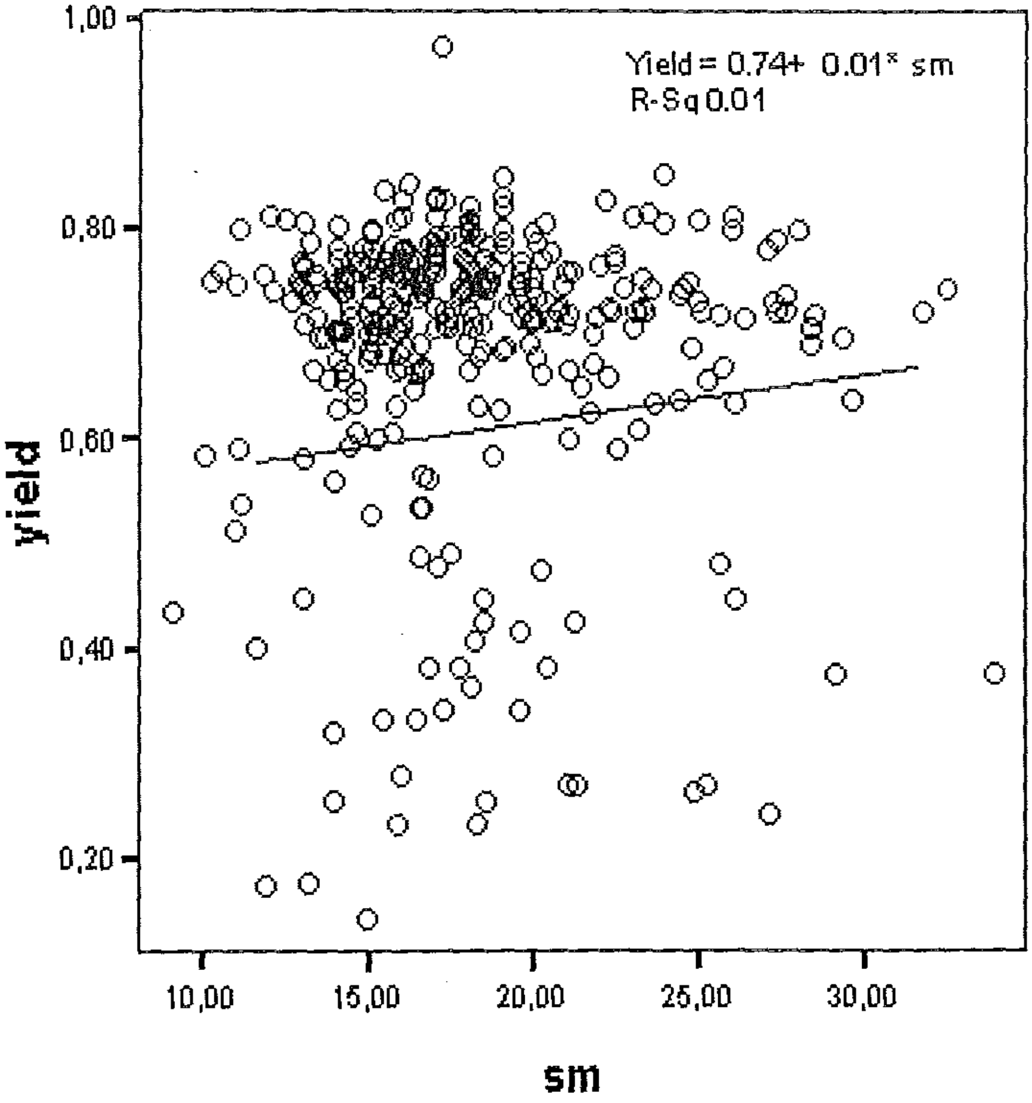


Fig. 22. Correlation between the yield (fluorescence yield) and sm (soil moisture content in percentage)

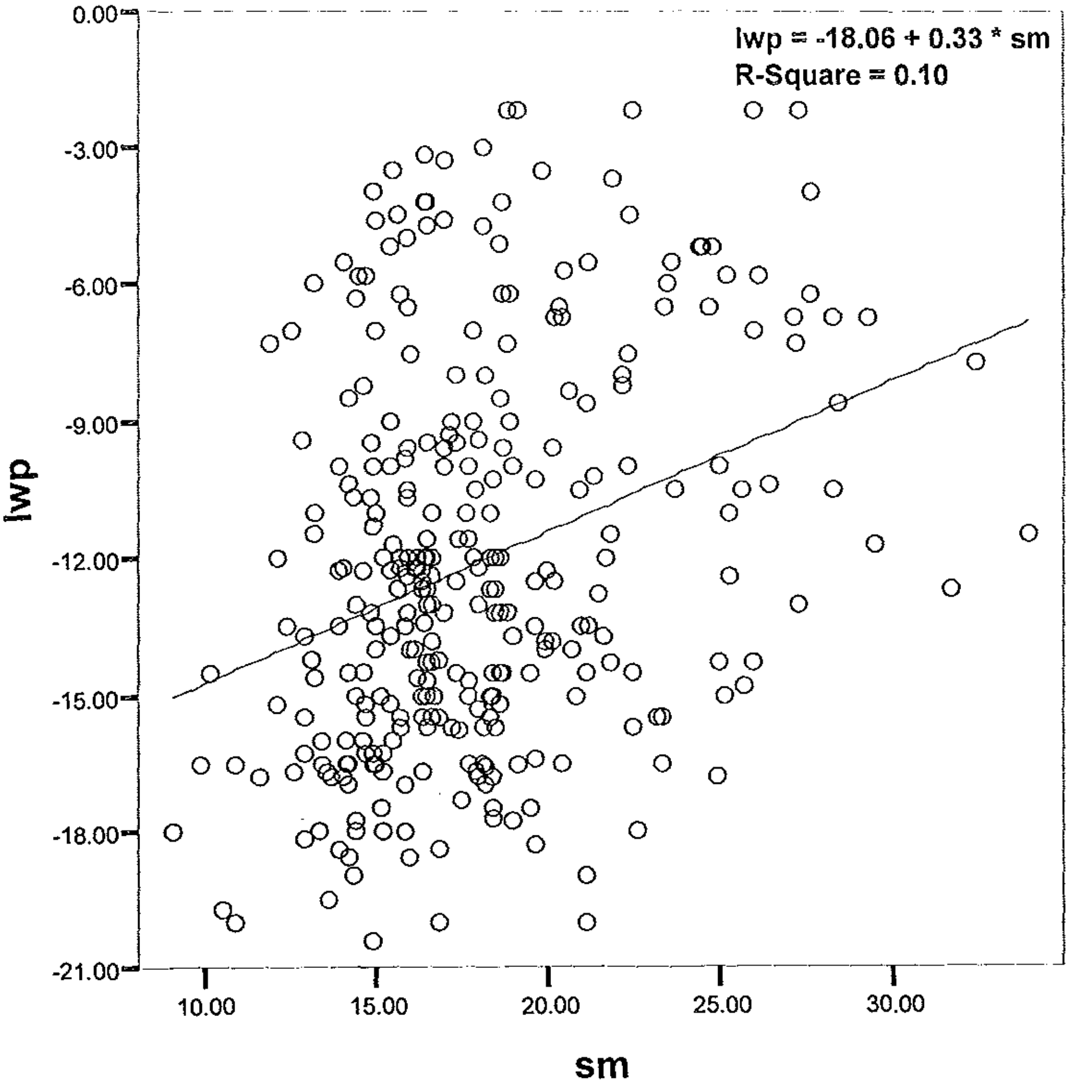


Fig. 23. Correlation between LWP (leaf water potential) and sm (soil moisture content).

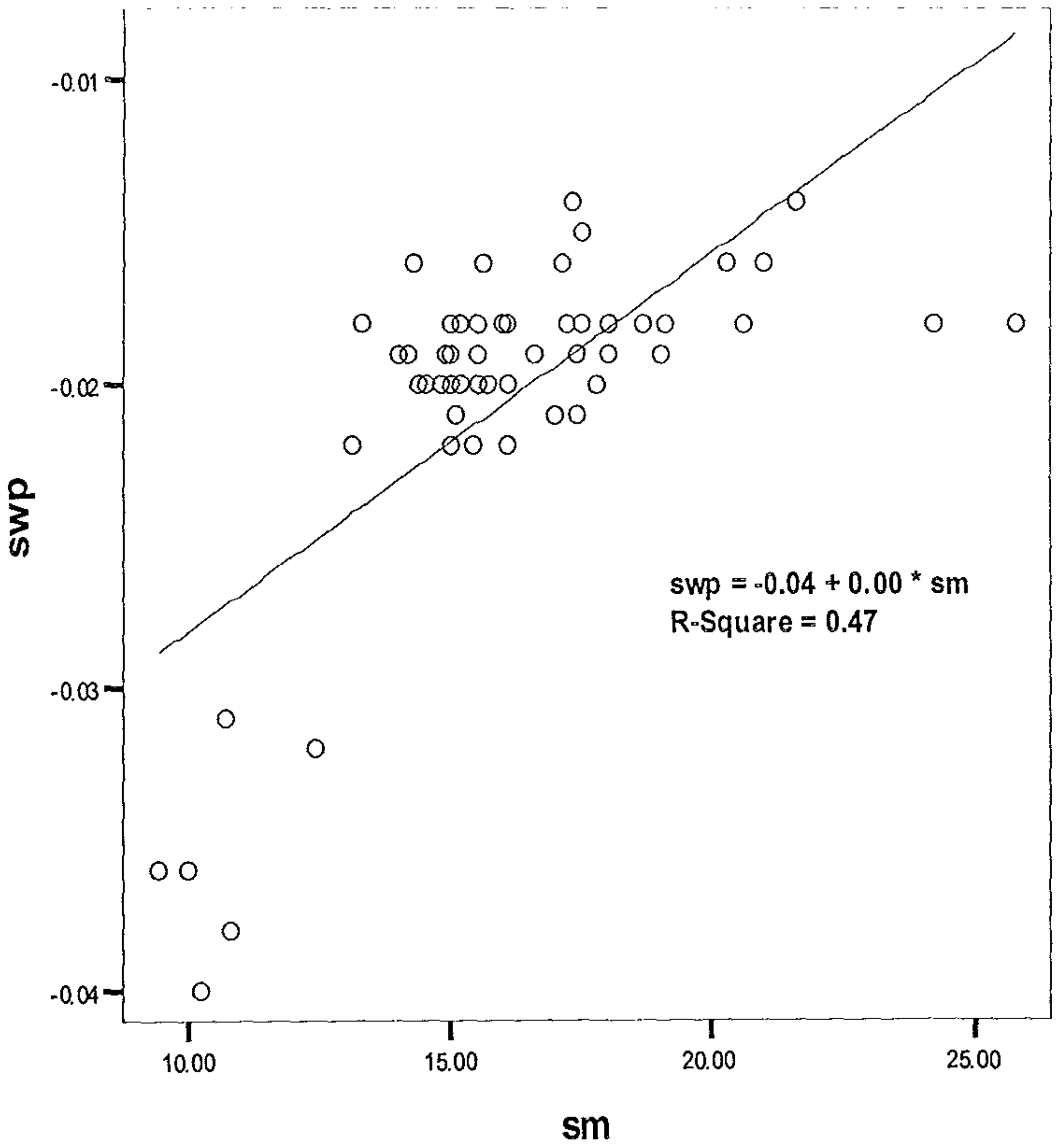


Fig. 24. Correlation between SWP (soil water potential) and sm (soil moisture content).

5. DISCUSSION

5.1 Soil water relations

5.1.1 Volumetric soil water content

In this study, different aspects of soil water relations were investigated. The variation of soil moisture at two distances from the individual coffee trees (0.05 m and 1 m) was measured to find out whether soil moisture decreased as a function of distance from the individual coffee tree. There was no significant difference between the two values, perhaps because of the interaction of the roots of other herbs, shrubs and big trees.

The soil moisture data clearly show some moisture gradients among the sites and sub sites especially in the dry season (Fig. 7A). In the wet season, all the sub sites had more or less similar soil moisture distribution. But the variation was significant in the dry season. It was also known that the wet and dry seasons' soil moisture values in all the sites were significantly different and maximum decrease was recorded in Sheko 3 (79 %) and minimum decrease in Bonga 2 (65%) which were the driest and the wettest sub sites respectively.

There could be some factors responsible for the soil moisture variations from certain area to the other. These might be the variation in the land-atmosphere exchange (Buckley, 2001), the soil properties like texture, organic matter content and water holding capacity of the soil (Abdal, *et al.*, 2002) and/or the land cover (Timbal *et al.*, 2001, 2003) of the regions. Soil moisture variability was also observed depending on the nature of shade. Relatively greater soil moisture content was observed in heavy shade than light shade (data not shown). Similarly, the amount of fallen plant materials covering the land surface (mulch) also affects the soil moisture contents depending whether there is thick or light mulch cover. Fallen leaves and other decayed plant materials like twigs are the main sources of mulch in forests.

In general, the grand mean soil moisture contents (of all the sites) in the wet and dry seasons were 47.91% and 17.33%, respectively. It has been believed (no data available) that there has been surplus water available for coffee growth in the coffee forest regions in Ethiopia. However, according to this soil moisture data, it seems that the soil water available is not so much sufficient as it is expected to be in the natural coffee forests so far studied probably due the current climatic changes. Therefore it could be suggested that the coffee populations in these areas generally experience water deficits.

5.1.2 Soil water potential (SWP)

Variation of SWP as a function of depth (0.15 m, 0.30 m and 1 m) measured in the wet season was not significant. This could also be mainly due to the more or less constant microclimatic environment of the forest soils. Sites with higher soil moisture content had also higher SWP values and vice versa.

5.2 Leaf water potential

In all of the sites, a midday depression of diurnal LWP values were found (between 13:00-14:00 h) and recovery started from 14:00 h (Fig. 13). The Bonga coffees had significantly highest LWP indicating that they are the least stressed populations because water stressed plants have lower LWP than unstressed plants (Zhang and Archord, 1993).

Midday and predawn LWP values were plotted with respect to a 45° central line bisecting the two axes following Mitloehner (2000) and interpreted with reference to it (Fig. 14). This line represents the points where predawn and midday LWP values are equal whereby permanent wilting of plant species takes place (Mitloehner, 2000; Kindeya Gebrehiowt, 2003). The values in all the sites in this case are above the bisecting line. Most of the plotted values of Yayu are the farthest values from the line followed by most of the values of Sheko which shows the highest recovery (the highest re-saturation capacity) for the Yayu populations followed by Sheko which could be a strategy for drought avoidance as also pointed out by Mitloehner (2000) and Kindeya Gebrehiwot (2003). In fact, for all the sites, there are significant diurnal ranges (P=0.01) as shown on Table 3 which could mean that drought adaptations are true for all the populations (Mitloehner, 2000; Kindeya Gebrehiowt, 2003). The minimum diurnal range (the least re-saturation) was measured in Bale. Therefore, it could be suggested that the Bale coffee populations use drought tolerance as a mechanism (rather than avoidance by re-saturating themselves) probably by regulating their stomata as a major mechanism. It seems that Bonga coffees are not too stressed to show some drought resistance characteristics at this particular time of measurement since both predawn and midday LWP values are very high.

5.3 Chlorophyll fluorescence

There was no significant difference between the older, younger and medium aged leaves ($p=0.05$) in terms of the effective quantum yield ($\Delta Fm/Fm'$) as shown on Fig 14. This is in line with the work of Murchie *et al.* (1999) who showed that the photosynthetic capacity of older and younger leaves was almost similar. Normally younger leaves perform better than older leaves as shown by Backhausen and Shceilde (1999) where the age class of the leaves is very distinct. Kitajima *et al.*, (2002) also showed that photosynthetic rate was negatively correlated with the age of the leaves. But in this case the age classes of the leaves were not very distinct. This is to say that the leaves were not selected from the very old or very young branches.

There were slight differences among the sub sites in terms of their photosynthetic performance as shown on Fig 15. Bale 1, Bonga 1, Sheko 1 and Yayu 3 showed highest values of fluorescence yield within their respective sites and midday depression was observed in all. The work of different investigators showed that fluorescence yield of all unstressed plant leaves is 0.83. But in our case, the maximum values were below 0.83, which could mean that the coffee populations are slightly water stressed.

Comparison of the wet and dry seasons' light response fluorescence yield at Bonga and Yayu sites was shown on Fig 19. In Bonga 1, Bonga 2 and Yayu 1 dry season's effective quantum yield was greater than that of the wet season but in the rest of the sub sites, no conspicuous differences were observed. However, the mean fluorescence yield of the dry season was greater than the wet season in both sites (see Appendix I). This comparison may not indicate the level of water stress for the two seasons. It could be accounted of different plant functions as a response to the intensive rain of the season which could have some effects on the rate of photosynthesis.

5.4 Comparison of sun and shade coffee trees

In almost all of the measurements, shade trees had greater values of chlorophyll fluorescence yields or effective quantum yield (ΔF/Fm'), maximal (Fm') and minimal (F) fluorescence than the sun exposed trees (Fig 18). This result is inline with the work of Griffin *et al.*, (2004) who showed that shade grown understorey trees have greater effective quantum yield than those grown in full sunshine. They also pointed out that shad-grown trees often have relatively large antenna complex for maximum light capture. According to Anderson *et al.*, (1997); Allen and Nilson (1997) and Thomas *et al.*, (1998), PSII plays a key role in regulating the molecular redox mechanisms in signaling for acclimation to environmental stresses including light. They discussed that plants must maintain active balance between the energy received and the energy utilized. According to Kloppstech (1997), the plant photosynthetic activities are gene regulated that are light controlled. It was discussed that chlorophyll formation as well as their corresponding appoprotiens are co-regulated and reduce formation of the dangerous radicals especially at higher level of light intensities (Anderson, *et al.*, 1991; Kloppstech, 1997; Krüger *et al.*, 1997; Adamska 1997). Valladares and Pearcy (1997); Apostol and Briantais (2003) and Schultz (2004) pointed out that the inhibition of flouresescence yield by high irradiance is enhanced by water stress. So we can see from the graphs (lower right of Figure 20) that Yayu coffees are more water stressed than that of Bale.

5.5 Correlations

The chlorophyll fluorescence yield was linearly (but weakly) correlated to both plant and soil water status. This was in line with the work of Juliol, *et al.*, (1993) and Eastman *et al.*, (1995) who showed that a progressive water stress in plants results down regulation of chlorophyll fluorescence yield. Eheleringer and Cook (1984) and Smithyman *et al.*, (2001) also investigated the photosynthetic responses of drought stressed plants and found out that fluorescence yield decreases linearly with decreasing leaf water potential. Similar results were also reported by Congming and Zhang (1999). According to Lawlor (1993), water stress induces stomatal closure as a mechanism to reduce the rate of transpiration which in turn inhibits the rate of photosynthesis. Apostol and Briantais (2003), and Baker and Rosenqvist (2004) pointed out that water deficit predisposes photoinhibitory damage to PSII indicating the effect of interaction of water stress and high light on PSII. Similar observations had also been reported by Marye *et al.*, (2002), Jagtap *et al.*, (1998) and Angelopoulos *et al.*, (1996). Matouskova *et al.* (1999) and Lu and Zhang (1999) pointed out that photosynthetic processes related to the thylakoid membrane structures are very resistant to drought but in case of PSII, a mild water stress can cause damage to it.

The hypothesis according to Marco *et al.*, (1993) is that in water stressed plants, the decease in the rate of photosynthesis results largely from the damage caused to chlorophylls and photosynthetic apparatus together with alteration of electron transport rate. According to Kramer (1983), when leaf water potential is lowered, the production of chlorophyll a/b proteins is inhibited which in turn inhibits chlorophyll accumulation associated with the loss of lamella which is the light harvesting chlorophyll a/b protein complex of chloroplast membrane. Libon *et al.*, (2003) pointed out the interdependence of the dynamics of leaf water potential, soil moisture and photosynthesis. So we could also conclude that fluoresce yield is an indicative of both plant and soil moisture status. This means that chlorophyll fluorescence yield increases with increasing soil moisture and leaf water potential and vise versa.

A relatively stronger positive correlation was seen between leaf water potential and soil water content than the effective quantum yield and leaf water potential or soil moisture. This is in agreement with the work of Zwack and Graves (1998) and Sellin (1997) who pointed out that low predawn leaf water potential reflects limited water available in the soil. Liang, *et al.* (2002) also showed that leaf water potential decreases with soil moisture content. So far, maximum correlation was seen between soil moisture and soil water potential. Both of these measurements, volumetric soil moisture content and soil water potential, are two different ways of measuring the same thing. That means, in both cases soil moisture level is measured basically with different principles. The volumetric soil moisture content is the expression of the soil moisture level as a proportion in a given volume of soil sample (percentage by volume). In case of soil water potential, the level of the available soil water is indirectly recorded by measuring the amount of pressure (tension) exerted or spent by the plant in order to absorb water from the soil. This means that for dry soils, lower volumetric soil moisture content, as well as lower soil water potential values are recorded than wet soils.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

Similar soil moisture distribution was found in Bonga, Sheko and Yayu in the wet season but variations were seen in the dry season. The dry season's soil moisture was about two-fold less than that of the wet season and the highest seasonal range was found in the driest sub site (Sheko 3) and the lowest in the wettest sub site (Bonga 2). The highest predawn LWP values were recorded in Bonga and Yayu, while the height midday values were recorded in Bonga and Bale for the dry season. Stressed coffee trees showed greater range between predawn and midday leaf water potential.

There were no significant differences in chlorophyll fluorescence yields between the different age groups of leaves. Significant differences were found between most of the sites and subsites in terms of their chlorophyll fluorescence yields. Shade coffees had a higher photochemical efficiency than sun exposed coffee trees. Likewise, dry season's photochemical efficiency was greater than that of the wet season.

In general, the evaluation of both plant and soil water status showed that Bale (Dolo Mena), Bonga, Sheko and Yayu forest and semi-forest coffees are slightly water stressed. It is obvious that the survival of plants (perhaps any living organism) in a given habitat would be questioned if it fails to adapt to the different types and levels of stresses (including water deficits). Thus, it could be suggested that the arabica coffee populations in the forests of Bale (Dolo Mena), Bonga, Sheko and Yayu have attained different strategies of adaptations to water deficits. It also seems that Sheko and Yayu coffees are drought avoiders and Bale coffees are drought tolerant. It is also assumed that the Bonga coffees were not too stressed to display some sorts of drought tolerance for the season. However more data are required to relate drought resistances in coffee to environmental parameters.

6.2 Recommendations

Based on the *in situ* experiments conducted, the following recommendations are suggested:

1. The low soil moisture content and low water potential, together with the low leaf water potential indicate water stress levels on the coffee populations. Therefore, necessary measures have to be taken in order to attain an increased soil moisture taking into account, especially the fact that soil moisture gradients within the sites (variations among the sub sites of a given site) tend to follow the levels of forest disturbances: the higher the disturbance the lower the soil moisture content and vise versa. The maintenance of the natural conditions of the forests will help much the regulation of soil moisture contents which is becoming a problem (in fact with other human factors) for the survival of the arabica coffee gene pool.

2. Farther investigations to find out traits that would incorporate both drought resistance and increased crop production in coffees, using more physiological parameters including growth, soil analysis and tests as well as more seasons are highly recommended.

3. Coffee benefits more in shade (perhaps light shade) than in full sun. Therefore, farmers or coffee growers benefit more from their coffee under cultivation in shade than in an open sun especially where soil moisture availability is sometimes a problem. In the case of severe water stress due to less soil moisture available, growers may need to irrigate their farms in addition to maintaining appropriate shades for their coffees.

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APPENDICES

Appendix 1. Statistical analysis of chlorophyll fluorescence of the wet and dry seasons in Bonga and Yayu coffee populations.

A. Bonga

Descriptive

	PAR	N	Mean Of yield	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	Upper Bound	Minimum	Maximum
DRY	.00	9	.7378	1.932E-02	6.439E-03	.7229	.7526	.70	.76
	35.00	9	.5262	6.140E-02	2.047E-02	.4790	.5734	.42	.58
	52.00	9	.4522	5.382E-02	1.794E-02	.4109	.4936	.34	.50
	85.00	9	.3712	7.751E-02	2.584E-02	.3116	.4308	.18	.44
	135.00	9	.2933	8.801E-02	2.934E-02	.2257	.3610	.14	.41
	212.00	9	.2101	8.310E-02	2.770E-02	.1462	.2740	.07	.34
	325.00	9	.1357	7.282E-02	2.427E-02	7.969E-02	.1916	.03	.26
	500.00	9	8.122E-02	4.540E-02	1.513E-02	4.633E-02	.1161	.02	.17
	750.00	9	.1528	.2256	7.521E-02	-2.0650E-02	.3262	.00	.61
	Total	81	.3290	.2236	2.485E-02	.2795	.3784	.00	.76
WET	.00	9	.6691	8.771E-02	2.924E-02	.6017	.7365	.52	.74
	35.00	9	.1774	.1448	4.828E-02	6.611E-02	.2888	.04	.38
	52.00	9	.1469	.1288	4.294E-02	4.787E-02	.2459	.04	.32
	85.00	9	.1112	.1086	3.621E-02	2.773E-02	.1947	.03	.26
	135.00	9	7.100E-02	8.496E-02	2.832E-02	5.696E-03	.1363	.01	.19
	212.00	9	4.044E-02	5.862E-02	1.954E-02	-4.6131E-03	8.550E-02	.00	.13
	325.00	9	2.267E-02	3.449E-02	1.150E-02	-3.8412E-03	4.917E-02	.00	.08
	500.00	9	1.011E-02	1.553E-02	5.176E-03	-1.8246E-03	2.205E-02	.00	.04
	750.00	9	1.667E-03	3.317E-03	1.106E-03	-8.8272E-04	4.216E-03	.00	.01
	Total	81	.1590	.2143	2.381E-02	9.157E-02	.1863	.00	.74

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
DRY	Between Groups	3.314	8	.414	43.365	.000
	Within Groups	.688	72	9.552E-03		
	Total	4.001	80			
WET	Between Groups	3.120	8	.390	50.753	.000
	Within Groups	.553	72	7.684E-03		
	Total	3.673	80			

(Continued...)

B. Yayu Descriptive

	PAR	N	Mean Of yield	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	Upper Bound	Minimum	Maximum
DRY	.00	9	.6754	5.602E-02	1.867E-02	.6324	.7185	.60	.73
	35.00	9	.5729	4.509E-02	1.503E-02	.5382	.6076	.51	.63
	52.00	9	.5421	4.473E-02	1.491E-02	.5077	.5765	.48	.61
	85.00	9	.5033	4.571E-02	1.524E-02	.4682	.5385	.43	.56
	135.00	9	.4780	8.042E-02	2.681E-02	.4162	.5398	.40	.67
	212.00	9	.3952	6.023E-02	2.008E-02	.3489	.4415	.31	.50
	325.00	9	.3088	5.502E-02	1.834E-02	.2665	.3511	.23	.38
	500.00	9	.2207	4.947E-02	1.649E-02	.1826	.2587	.14	.28
	750.00	9	.1360	3.874E-02	1.291E-02	.1062	.1658	.08	.18
	Total	81	.4258	.1744	1.938E-02	.3873	.4644	.08	.73
WET	.00	9	.6873	7.361E-02	2.454E-02	.6307	.7439	.60	.77
	35.00	9	.3640	.1016	3.388E-02	.2859	.4421	.28	.50
	52.00	9	.3087	.1192	3.972E-02	.2171	.4003	.20	.46
	85.00	9	.2427	.1262	4.206E-02	.1457	.3396	.14	.41
	135.00	9	.1767	.1279	4.262E-02	7.839E-02	.2749	.08	.35
	212.00	9	6.933E-02	3.423E-02	1.141E-02	4.302E-02	9.565E-02	.04	.11
	325.00	9	5.267E-02	5.623E-02	1.874E-02	9.441E-03	9.589E-02	.01	.13
	500.00	9	2.667E-02	4.000E-02	1.333E-02	-4.0801E-03	5.741E-02	.00	.08
	750.00	9	1.500E-02	2.250E-02	7.500E-03	-2.2950E-03	3.230E-02	.00	.05
	Total	81	.2159	.2226	2.473E-02	.1667	.2651	.00	.77

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
DRY	Between Groups	2.222	8	.278	94.937	.000
	Within Groups	.211	72	2.926E-03		
	Total	2.433	80			
WET	Between Groups	3.414	8	.427	55.947	.000
	Within Groups	.549	72	7.628E-03		
	Total	3.963	80			

Appendix 2. Descriptive statistics of soil moisture measured at 0.5 m and 1 m distances

Distance (m)	No. of sample	Minimum sm (%)	Maximum sm (mm)	Mean	Std. Dev.	Variance
0.5	144	12.5	57.30	40.89	11.99	143.86
1	144	11.7	58.60	42.09	12.14	147.50

Appendix 3. Descriptive statistics of SWP at different depths

Depth (m)	No. of samples	Minimum swp (bar)	Maximum swp (bar)	Mean	Std. dev.	Std.error Mean
0.15	12	-0.32	-0.013	-0.0121	-0.095	-0.028
0.30	12	-0.32	-0.013	-0.0123	-0.094	-0.027
0.45	12	-0.33	-0.01	-0.0125	-0.01	-0.029

Appendix 4. Case Summaries Report: Soil moisture, Leaf water potential and Effective quantum yield

				SM	LWP	YIELD
TIME	1.30	1		16.30	-16.70	.77
		2		15.80	-17.00	.76
		3		17.70	-16.50	.74
		4		17.70	-14.70	.38
		5		16.00	-14.00	.28
		6		13.10	-14.20	.74
		7		16.80	-18.40	.38
		8		16.80	-14.20	.38
		Total	N	8	8	8
	2.30	1		16.20	-12.20	.77
		2		15.40	-13.70	.76
		3		18.60	-14.50	.75
		4		18.60	-15.20	.26
		5		18.30	-15.50	.23
		6		13.40	-16.00	.75
		7		13.90	-18.40	.32
		8		13.90	-12.30	.26
		Total	N	8	8	8
	3.30	1		17.00	-13.20	.78
		2		12.90	-13.70	.77
		3		16.60	-14.30	.74
		4		16.60	-12.40	.53
		5		16.40	-13.40	.33
		6		14.10	-16.50	.74
		7		16.50	-15.70	.49
		8		16.50	-12.00	.53
		Total	N	8	8	8
	4.30	1		16.10	-12.20	.78
		2		13.90	-13.50	.74
		3		19.60	-13.50	.76
		4		19.60	-10.30	.75
		5		15.90	-12.40	.70
		6		14.70	-15.50	.76
		7		18.40	-15.00	.75
		8		18.40	-10.30	.75
		Total	N	8	8	8
	5.30	1		16.00	-14.00	.77
		2		16.30	-12.70	.77
		3		19.60	-12.50	.77
		4		19.60	-18.30	.34
		5		18.40	-17.50	.71
		6		14.40	-17.80	.77
		7		17.30	-14.50	.72
		8		17.30	-12.50	.34
		Total	N	8	8	8
	6.30	1		17.30	-10.70	.83
		2		17.00	-7.00	.83
		3		17.00	-9.60	.83
		4		19.00	-3.30	.82
		5		18.00	-4.20	.81
		6		19.00	-3.20	.83
		7		19.00	-6.30	.85
		8		18.00	-6.30	.82
		9		18.00	-5.80	.81
		Total	N	9	9	9
	7.30	1		16.00	-10.70	.81
		2		16.00	-8.20	.81

(Continued...)

	3		16.00	-10.00	81
	4		16.00	-4.00	.78
	5		17.00	-4.70	.79
	6		17.00	-5.00	.81
	7		18.00	-9.00	.81
	8		17.00	-5.20	.78
	9		18.20	-8.00	.79
	Total	N	9	9	9
8.30	1		17.30	-9.50	.79
	2		13.20	-11.00	.79
	3		15.00	-10.00	.78
	4		15.00	-4.60	.75
	5		15.00	-4.60	.75
	6		16.00	-4.50	.78
	7		17.00	-10.40	.77
	8		14.20	-8.50	.75
	9		12.80	-9.40	.75
	Total	N	9	9	9
9.30	1		18.00	-12.20	.78
	2		13.00	-11.00	.76
	3		14.00	-14.30	.75
	4		14.00	-4.20	.74
	5		15.00	-3.00	.71
	6		15.00	-6.20	.75
	7		18.00	-15.30	.76
	8		14.00	-9.40	.74
	9		13.00	-12.00	.71
	Total	N	9	9	9
10.30	1		14.70	-15.20	.77
	2		15.90	-12.00	.77
	3		16.00	-14.50	.74
	4		14.00	-4.20	.67
	5		16.50	-11.60	.66
	6		14.20	-14.50	.74
	7		14.90	-16.50	.68
	8		14.90	-16.30	.67
	Total	N	8	8	8
11.30	1		16.70	-15.00	.75
	2		15.70	-15.70	.76
	3		15.00	-15.00	.74
	4		18.30	-12.70	.63
	5		18.50	-12.70	.45
	6		12.90	-15.50	.74
	7		15.80	-18.00	.67
	8		15.80	-17.00	.63
	Total	N	8	8	8
12.30	1		15.10	-15.00	.75
	2		14.20	-16.50	.75
	3		14.00	-15.50	.70
	4		16.60	-13.00	.66
	5		16.30	-12.50	.65
	6		15.80	-13.50	.70
	7		14.20	-18.60	.69
	8		14.20	-14.50	.66
	Total	N	8	8	8
Total	N		100	100	100

Appendix 5. Case summary report of wet and dry seasons' soil moisture

SITE	SUB SITE	WET	DRY
2.00[b]	1.00		
	Mean	46.88	18.00
	Minimum	39.40	16.90
	Maximum	52.20	19.93
	Variance	15.23	1.07
	2.00		
	Mean	50.18	17.54
	Minimum	46.00	15.60
	Maximum	54.30	19.40
	Variance	4.82	2.19
	3.00		
	Mean	48.22	23.15
	Minimum	42.90	20.55
	Maximum	57.30	25.25
	Variance	12.07	2.57
3.00[c]	1.00		
	Mean	46.05	23.28
	Minimum	41.80	20.03
	Maximum	49.10	25.17
	Variance	5.88	2.73
	2.00		
	Mean	47.43	16.71
	Minimum	38.50	12.10
	Maximum	52.90	19.40
	Variance	15.95	3.19
	(Continued...)		
	3.00		
	Mean	45.44	.
	Minimum	39.60	.
	Maximum	48.80	.
	Variance	10.34	.
4.00[d]	1.00		
	Mean	48.52	15.15
	Minimum	45.70	13.30
	Maximum	50.70	18.20
	Variance	2.42	2.73
	2.00		
	Mean	48.48	13.02
	Minimum	45.70	10.73

(Continued...)

Maximum	50.30	15.03
Variance	2.58	1.40
3.00		
Mean	50.02	19.32
Minimum	46.40	16.13
Maximum	54.20	21.37
Variance	7.22	2.21
Grand Total		
Mean	41.43	17.59
Minimum	12.50	10.73
Maximum	57.30	25.25
Std Dev	11.93	3.42
Variance	142.43	11.72

b = Bonga, c = Sheko, d =Yayu

Appendix 6. Case summary report of predawn and midday leaf water potential

SITE	SUB SITE		PREDAWN	MIDDAY
1.00[a]	1.00			
		Mean	-6.11	-14.67
		Minimum	-11.00	-16.50
		Maximum	-3.70	-12.00
		StdDev	2.62	1.58
		Variance	6.86	2.50
	2.00			
		Mean	-3.59	-11.74
		Minimum	-5.50	-14.70
		Maximum	-2.50	-9.70
		StdDev	1.04	2.01
		Variance	1.08	4.04
	3.00			
		Mean	-7.56	-17.43
		Minimum	-10.00	-18.40
		Maximum	-5.80	-15.50
		StdDev	1.90	1.67
		Variance	3.62	2.80
2.00[b]	1.00			
		Mean	-3.00	-13.54
		Minimum	-3.50	-15.60
		Maximum	-2.00	-12.50
		StdDev	.62	1.02
		Variance	.39	1.05
	2.00			
		Mean	-2.99	-9.49
		Minimum	-4.50	-12.30
		Maximum	-2.30	-7.60
		StdDev	.73	1.54
		Variance	.53	2.37
	3.00			
		Mean	-2.39	-10.10
		Minimum	-3.00	-12.70
		Maximum	-2.00	-8.60
		StdDev	.34	1.37
		Variance	.11	1.88
3.00[c]	1.00			
		Mean	-5.23	-16.29
		Minimum	-9.00	-18.00
		Maximum	-3.70	-14.50
		StdDev	2.08	1.55
		Variance	4.31	2.40

(Continued...)

3.00[c]	2.00		
	Mean	-8.67	-18.93
	Minimum	-11.80	-20.00
	Maximum	-6.50	-18.00
	StdDev	2.05	.67
	Variance	4.21	.45
	3.00		
	Mean	.	.
	Minimum	.	.
	Maximum	.	.
	StdDev	.	.
	Variance	.	.
4.00[d]	1.00		
	Mean	-2.87	-15.69
	Minimum	-3.50	-18.60
	Maximum	-2.20	-13.50
	StdDev	.57	1.61
	Variance	.32	2.58
	2.00		
	Mean	-10.44	.
	Minimum	-15.70	.
	Maximum	-5.40	.
	StdDev	4.31	.
	Variance	18.59	.
	3.00		
	Mean	-3.26	-17.91
	Minimum	-4.00	-19.70
	Maximum	-2.60	-13.50
	StdDev	.52	2.26
	Variance	.27	5.09
Grand Total			
Mean		-5.10	-14.41
Minimum		-15.70	-20.00
Maximum		-2.00	-7.60
StdDev		3.18	3.48

a= Bale, b = Bonga, c = Sheko, d =Yayu