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The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees[1]

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ABSTRACT

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Faidherbia albida is an important tree species in traditional agroforestry cropping systems of the Sahel. The enhanced crop growth under its canopy (the '*albida* effect') has been attributed to increased soil fertility in the canopy zone, improved microclimate, particularly in relation to plant/soil water relations, and the fact that the tree sheds its leaves in the rainy season, which reduces shade and allows the crops to grow. The present studies demonstrate that shade-induced reduction of soil temperatures, particularly at the time of crop establishment, contributes to the better growth under these trees. Greater use of shade to reduce soil temperature to the benefit of crops is proposed.

Vertical shade barriers were used to vary the soil surface temperature by varying the time that the soil was exposed to direct sunlight. Pearl millet (*Pennisetum glaucum*), sown in this range of environments, germinated and grew best in a partially shaded environment, but failed in fully exposed conditions; growth was inversely related to mean soil surface temperatures during seedling establishment. In a separate, concurrent study, at the beginning of the Sahelian rainy season, a nearly leafless tree canopy intercepted about half of the incoming radiation, which resulted in a decrease of up to 10°C in the maximum soil temperature at 2 cm depth (depending on position relative to the tree and time relative to rain) during the seedling establishment phase.

INTRODUCTION

Faidherbia albida (Del.) A. Chev. is a leguminous tree species found throughout semi-arid Africa, from Senegal to Ethiopia and south to the Limpopo River system and Angola/Namibia. In West Africa it is an important part of traditional 'parkland', or two storey, cropping systems (Vanden-

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beldt, 1990). Numerous authors have noted that crop growth under the trees is superior. Dancette and Poulain (1969), for example, found a two-fold yield increase in sorghum (*Sorghum bicolor*), and a 30% yield increase in groundnut (*Arachis hypogaea*), under the tree canopies compared with yields away from the trees.

This '*albida* effect' has most often been attributed to a nutrient effect, in which nutrients taken up by the tree's roots, or fixed by symbionts, are deposited on the soil surface through litterfall (Centre Technique Forestier Tropical, 1988). Livestock sheltering from the sun may also add considerable quantities of nutrients to the shaded zone. Soils under these trees often have impressively better nutrient status and physical characteristics compared with soils away from the trees (Charreau and Vidal, 1965; Dancette and Poulain, 1969). However, recent evidence (Geiger et al., 1992) has confirmed the idea of Sanchez (1987) that some improved soil factors may in fact precede the tree. A few authors have reported evidence of improved microclimate under the tree canopies in *F. albida* parklands (Schoch, 1966; Dancette and Poulain, 1969), or in wooded savannah (Belsky et al., 1989), but no attempt has been made to separate the physical and nutritional effects of these trees on crop performance.

Another reason cited in the literature for the *albida* effect is the curious phenology of the tree. Typically, *F. albida* supports its leaves in the dry season (October–April) and defoliates shortly before the rains (March–April); defoliation is usually complete for much of the rainy season. Although no systematic measurements have been reported, most authors have viewed this leafless stage as advantageous to crops, primarily because shading is not deemed severe enough to cause reductions in crop yield.

In the Sahel, farmers usually sow pearl millet in hand-dibbled pockets with the first rains in May/June. If successful, early sowing takes full advantage of the rather short growing season. However, survival of germinating plantlets is determined by the amount of time to the next rain event, which is extremely unpredictable in the early growing season (Sivakumar, 1986). Considerable evidence exists that soil surface temperatures (which may exceed 60°C during the seedling establishment phase) are often responsible for failure of the crop to survive when the first rains are followed by periods of high temperature and radiation (Soman et al., 1986). Ong and Monteith (1984) have demonstrated that germination and plumule extension in pearl millet are strongly influenced by temperature, with the optimum temperature for these processes being between 30° and 35°C. Above this optimum, germination and shoot elongation rates decline linearly, and rapidly.

Peacock et al. (1990) have shown that the temperatures observed at the soil surface in the Sahel can result in thermally induced death of any nearby phloem vessels. Heat girdling prevents translocation of assimilates to the roots and results in plant death, even though there may still be water available in the root zone. There is little information on the effect of temperatures close to the lethal levels on the subsequent growth of the crop plant.

The present experiments were conducted to examine the effect of variations in soil temperatures on millet seedling establishment and early growth, and to determine the effect of shade from partially defoliated *F. albida* trees on the crop seedling establishment environment.

MATERIALS AND METHODS

The experiments were conducted during 1990 at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center (ISC), Sadore, Niger, 45 km south of Niamey which is at 13°N, 2°E. The soil at the site is part of the Labucheri series and is classified as Psammentic Paleustalf; sandy, siliceous and isohyperthermic according to the US Soil Taxonomy (West et al., 1984). The mean total annual rainfall is approximately 560 mm year^{-1}, but was 400 mm in the year of this study.

The studies were established in May 1990. The first study described three transects in the vicinity of a mature *F. albida* tree. The tree had a height of 8.5 m, a diameter of 0.57 m at 1.3 m height, and an average canopy diameter of 12.3 m. Height to the bottom of the canopy was 3.5 m.

Transects were laid out to the north, southeast and southwest of the base of the trunk. Thermocouples were buried in the soil along each transect (at depths of 2 cm) 2 m from the base of the tree and 2 m outside the canopy area of the tree. Two full spectrum solar radiation sensors (Delta T Devices, Cambridge, UK) were installed 30 cm above the soil to measure incoming radiation, one on the north transect 2 m from the trunk and the other 10 m outside the canopy due south of the trunk. Readings from thermocouples and radiation sensors were taken every 20 s, averaged every 15 min and stored utilising a data logger (Campbell Scientific Instruments, Logan, UT). For this report, temperature data of the day before a 20 mm storm at 05:00 h on 23 May will be compared with data taken the day after the storm to compare the effect of the shade on soil temperatures with dry and wet soil surfaces. Typical differences in the radiation under and outside the canopy are provided by the data of 25 May, which was a largely cloudless day.

To test the effect of different periods of shade on establishment and early growth of pearl millet, a 1 m high fence made of millet stalk mats ('secou') was erected running in a north–south direction. The fence created shade of varying duration depending on the distance from its base. Establishing these artificial shade plots away from the shade of the tree effectively removed any confounding effects of soil fertility differences around the tree.

Plots consisted of three rows, each 5 m long, at right angles to the fence. These were divided into subplots, each of 0.5 m length, which varied in their distance from the fence. Two varieties of pearl millet (cultivars CIVT and

MBH 110) were sown on 18 May 1990 at 2.5 cm intervals in the rows, on both sides of the fence. The experiment was germinated with a 40 mm irrigation, this water application being followed by two storms (20 mm on 23 May, and 43 mm on 30 May). Soil surface temperatures were measured during the day over the first 3 weeks of growth using an infra-red thermometer (Teletemp, Fullerton, CA) every 2 h at stations located in each subplot. Each plot was replicated four times. The millet was allowed to grow for 6 weeks and then the shoot mass was harvested, oven dried and weighed.

RESULTS

Soil surface temperatures in the 'shade fence' experiment were strongly influenced by time (since the last rain) and position relative to the fence. As expected, recent rain resulted in lower soil surface temperatures, but this effect was of short duration because of rapid drying. Where little shade occurred, the soil surface temperatures followed typical diurnal patterns of temperature, regularly exceeding 50°C. While the soil surface was shaded by the fence the soil surface temperatures were considerably lower than the control plots, but once exposed to sunshine these temperatures rapidly rose to levels close to that of the control. However, the time for which these temperatures prevailed was a function of distance from the fence, and the combined effects of location and time of day are well integrated into the mean temperature. Mean daytime soil surface temperature at the base of the fence was 43.3°C, while the surface temperature of the fully exposed soil was 46.6°C.

Millet varieties did not differ significantly in their growth across the shade gradient. The millet plants 3.5 m from the fence did not survive the effects of high soil temperature for more than 10 days after emergence. Growth varied in a linear fashion between this point and the fence, being positively influenced by the duration of shade (Fig. 1), and inversely correlated with the mean soil surface temperature (Fig. 2).

Temperature at 2 cm depth in the uncropped soil under the tree canopy was also reduced by the decreased incident radiation, diurnal patterns depending on the movement of the tree's shadow. On 22 May, the day before the 20 mm storm, the 2 cm soil maximum temperatures were between 45° (southeast transect) and 50°C (southwest transect) outside the canopy but only 40°C inside the canopy (Fig. 3(a)). After the storm, soil temperatures were reduced because of wetting and soil surface evporation, reaching a maximum of 45°C outside the canopy on the southwest transect, which received afternoon sun (Fig. 3(b)), whereas soil temperatures under the canopy, where only morning sun was received (on the southeast transect), reached a maximum of 35°C. These differences associated with position about the tree were typical of those observed over the 6 day interval between storms.

Differences in radiation measurements in and outside the canopy are shown

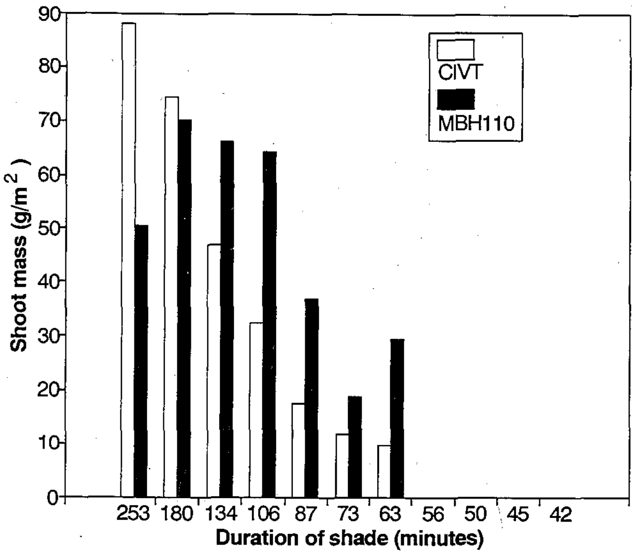

Fig. 1. Shoot biomass of pearl millet 6 weeks after sowing as influenced by cultivar and duration of shade.

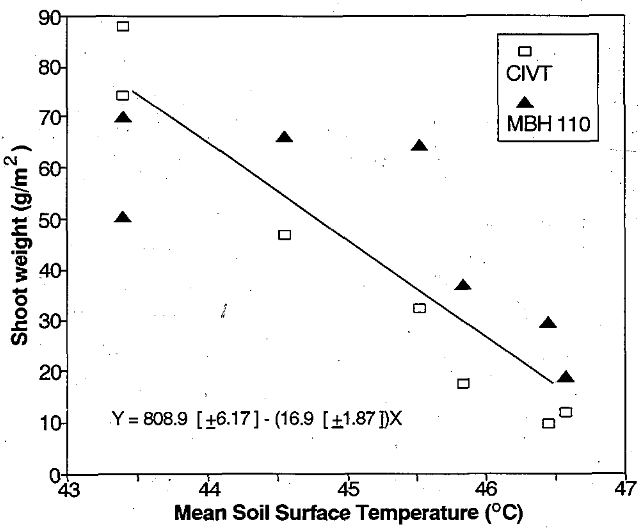

Fig. 2. Shoot biomass of pearl millet 6 weeks after sowing related to mean soil surface temperatures at Sadoré, Niger.

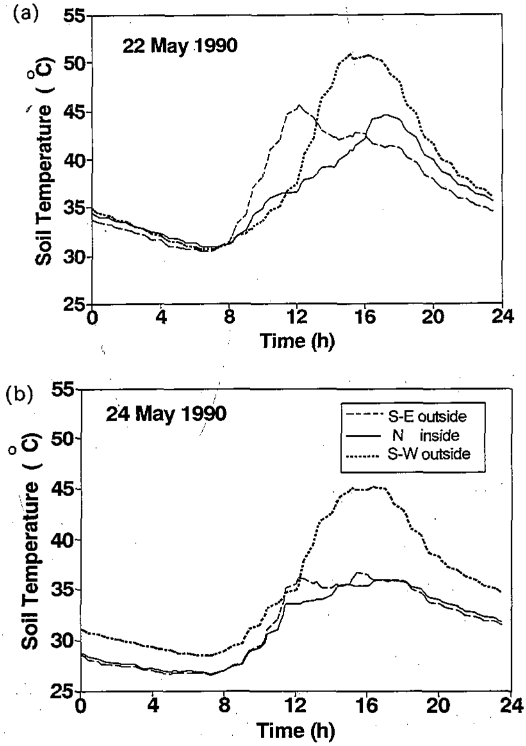

Fig. 3. Soil temperature at 2 cm depth inside and outside a *F. albida* tree canopy the day before (a) and the day after (b) a 20 mm storm. Sadoré, Niger.

in Fig. 4. The radiation measured on the relatively cloudless day of 25 May follows a diurnal pattern typical for the period between storms. Radiation measurements under the canopy were more uneven because of heavy shading by large branches from time to time during the day. Daily total radiation for

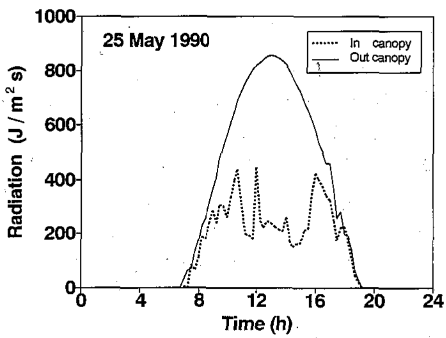

Fig. 4. Solar irradiance measured under and outside the canopy of a *F. albida* tree. Sadoré, Niger.

the period between storms averaged 20.3 $\pm$ 1.1 MJ m^{-2}. Average maximum air temperature for this period was 40.4 $\pm$ 1.7°C.

DISCUSSION

It would seem that the modification of the soil temperature at the time of seedling establishment is an important component of the '*albida* effect' that has not previously been recognised. The canopy of the tree caused considerable reduction in the (2 cm) soil temperatures, which were reduced to levels closer to the optimum for pearl millet germination and growth.

The variations in millet growth within the shade-fence experiment, without the confounding effect of the fertility differences around the tree, were most probably caused by the effects of soil surface temperature rather than the primary effects of water deficits. The strong linear relationship observed between shoot growth and soil surface temperature suggests that temperatures approaching the lethal value, for some period, do limit survival and retard subsequent growth. This may be the result of damage to the phloem based translocation to the roots (as suggested by Peacock et al., 1990), or reduction in the development of roots (Stomph, 1990) which would then fail to advance beyond the drying front. The results indicate that, without the companion effect of decreased temperature under the *F. albida*, the millet crop would not be able to exploit the greater fertility associated with this tree species.

In previous studies of the factors contributing to the '*albida* effect', the effect of the tree on air temperature has been found to be small (Dancette and Poulain, 1969), probably because advective heat transfer from nearby unshaded areas is a major factor in determining the air temperature under the canopy. The lower radiation load on millet under the canopy may be expected to result in less water use. If water deficits develop, the lower radiation load on leaves under the canopy should be significant in maintaining smaller canopy/air temperature differences.

There are several implications of this finding to Sahelian agriculture. Firstly, one must expect that there will be considerable variation in the canopy of *albida* trees. Future research should seek to establish the optimum branch density to maximise production of the crop by balancing the benefits of temperature manipulation relative to the adverse effects of light reduction on photosynthesis. These experiments also indicate that the '*albida* effect' may allow the introduction of crops presently considered inappropriate to the Sahelian zone because they cannot tolerate the prevailing temperatures. Secondly, where there are no trees, practices that may decrease soil temperatures such as tree planting, or mulches, should increase the yields. However, as *F. albida* seems to establish where there is already an 'island of better fertility' (Geiger et al., 1992), increasing the numbers of trees presents a considerable challenge. If other methods of providing local soil shading can be devised, however, then some part of the '*albida* effect' could be extended to areas away from existing trees.

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