

Chapter 13 D

Agrometeorology of Pearl Millet Production

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I. Importance of pearl millet in various climates

Pearl millet is a widely grown rainfed cereal crop in the arid and semi-arid regions of Africa and southern Asia. In other continents it is grown under intensive cultivation as a forage crop. Pearl millet is a crop of hot and dry climates, and can be grown in areas where rainfall is not sufficient (200-600 mm) for maize and sorghum. Primarily a tropical plant, pearl millet is often referred to as the “Camel”, because of its exceptional ability to tolerate drought. Even with minimal rainfall millet will typically still produce reasonable yields. In many areas where millet is the staple food, nothing else will grow. Besides providing food for human, millet stems are used for a wide range of purposes, including: the construction of hut walls, fences and thatches, and the production of brooms, mats, baskets, sunshades, etc (IFAD, 1999).

Pearl millet (*Pennisetum glaucum* (L) R. Br.) is one of the four most important cereals (rice, maize, sorghum and millets) grown in the tropics (The Syngenta Foundation for Sustainable Agriculture, 2002). It is believed to have descended from a West African wild grass which was domesticated more than 40,000 years ago (National Research Council, 1996). It spread from there to East Africa and then to India. Today millet is a food staple for more than 500 million people. Areas planted with pearl millet are estimated at 15 million hectares annually in Africa and 14 million hectares in Asia. Global production exceeds 10 million tons a year (National Research Council, 1996). The food value of pearl millet is high. Trials in India have shown that pearl millet is nutritionally superior from human growth when compared to maize and rice. The protein content of pearl millet is higher than maize and has a relatively high vitamin A content.

In addition to tolerating hot and dry climates, pearl millet is able to produce reasonable yields on marginal soils, where other crops would fail. Low fertility and high salinity are frequent problems in millet producing

areas. At the same time, pearl millet responds very favorably to slight improvements in growing conditions such as irrigation and tillage (Leisinger et al., 1995). For these reasons it has the potential to spread to more areas of the world, namely the semi-arid zones of Central Asia and the Middle East, North and South America, and Australia (National Research Council, 1996).

Pearl millet is grown by millions of resource-poor, subsistence level farmers (IFAD, 1999). The percentage of millet used for domestic consumption is rising steadily in Africa (World Bank, 1996). Pearl Millet is the third major crop in sub-Saharan Africa, with the major producing countries being Nigeria, Niger, Burkina Faso, Chad, Mali, Mauritania and Senegal in the west; Sudan and Uganda in the east. In Southern Africa, maize has partially or completely displaced millet because of the predominance of commercial farming.

Pearl millet, which accounts for about two-thirds of India's millet production, is grown in the drier areas of the country, mainly in the states of Rajasthan, Maharashtra, Gujarat, Uttar Pradesh and Haryana (FAO, 1996). In Pakistan, pearl millet is an important grain crop, especially in areas where drought is common. Millet is grown primarily south of latitude 34° N. Sixty percent of the area is in Punjab; 37.8 percent in Sindh. Ninety percent of the grain produced is used as food and as seed. The little surplus is sold mainly as seed to producers who grow millet for fodder and do not have seed of their own (Pakistan Agriculture Research Council, 2006).

Outside Africa and India, millets are also grown in China, The Russian Federation, Mexico, Australia, Canada and the United States of America. In most of these other countries, pearl millet is grown primarily as a forage crop for livestock production (National Research Foundation, 1996; The Syngenta Foundation for Sustainable Agriculture, 2003).

II. The Influences of Agroclimatological Variables on Pearl Millet

The climate of most pearl millet producing areas can typically be described as hot and dry. Pearl millet has become the primary staple food crop in

these areas because nothing else will produce a crop on a reasonably consistent basis. Five climatic factors are of particular importance to pearl millet production: rainfall, air and soil temperatures, daylength (photoperiod), radiation and wind. The impact of these variables is dependent on the developmental stage of the crop.

The development of pearl millet can be broadly divided into three growth stages (Begg, 1965):

GS¹: Growth stage one or sowing to panicle differentiation

GS²: Growth stage two or panicle initiation to flowering (floral induction)

GS³: Growth stage three or flowering to grain maturity

Rainfall:

Millet production depends almost entirely on rainfall as its moisture supply. Therefore the amount and distribution of rainfall are important factors in determining the ultimate productivity of the crop. In West Africa, the onset of the rainy season is highly variable while the end of the rains is sharp (Kowal and Kassam, 1978). Some of the agroclimatic features of rainfall distribution include:

- o Total rainfall during a season;
- o The onset of the rainy season;
- o The termination of the rainy season;
- o The distribution of rainfall during the rainy season, particularly early in the growth cycle.

Sowing and Emergence: Poor soil moisture at sowing reduces seedling emergence leading to poor crop establishment. In addition there can be extended periods between the initial rainfall and subsequent rains. If a poor stand results, farmers often re-sow when rains re-occur. Therefore, it is important that agroclimatic information include information not only on the onset of the rains but also the expected weather during the period immediately following the onset of the rainy season.

Vegetative growth: Intermittent breaks in rainfall are a common feature of the climate of millet producing areas. However the crop is well adapted to water deficits during the GS₂ period (Mahalakshmi et al., 1988).

Reproductive stage: Early flowering and grain filling stages are the most sensitive stages to water deficits (Mahalakshmi and Bidinger, 1985; Mahalakshmi et al., 1988). Both timing of stress in relation to flowering and intensity of stress determine the reduction in grain yield (Mahalakshmi et al., 1988). Most of the variation among environments in a multi-location trial was due to the availability of water during early grain filling.

Temperature:

Numerous studies have been carried out over the years on the effects of air and soil temperatures on the germination, growth and yield of pearl millet (Ong, 1983a; Ong, 1983b; Gregory, 1983; Khalifa and Ong, 1990). Pearl millet development begins at a base temperature around 12 °C, an optimum temperature between 30-35 °C and a lethal temperature around 45 °C). The base temperature has been shown to be fairly constant regardless of the stage of development (Ong, 1993a).

In the Sahel, temperatures are usually high because of high radiation load and scarce rainfall. However, in some parts of India soil temperatures can be a concern. Soil temperatures influence all aspects of early vegetative development, the emergence of seedlings, the initiation, appearance and final number of leaves and tillers (Ong, 1993a).

Germination and Emergence: (GS1) As noted earlier, soil temperatures must reach 12°C for germination to begin. The germination rate increases linearly with temperature to a sharply defined optimum of 33 °C and then drops sharply as temperatures increase (Ong, 1993a). High temperatures (>45 °C) and soil surface crusting following sowing may also result in poor crop establishment due to seedling death (Soman, et.al., 1987). In West Africa the problem is further complicated by sand blasting and the burying of young seedlings under the sand.

Development: GS2: Temperature requirements of pearl millet depend on the cultivar. Diop (1997) found an optimum range of 22 to 35 C for plant growth and a maximum of 45 to 40 C. The optimum temperature for root elongation is 32 °C. In OMM (1993), it is stated that pearl millet requires temperatures between 22 and 36 C for a good photosynthetic response, with an optimum range of 31 to 35 °C.

Cantina (1995) indicated that leaf appearance and expansion rates are positively correlated with temperature and the leaf area index (LAI increases linearly with temperature in the optimum range. Tillers appear sooner and they form more rapidly as temperature increases to about 25 °C (Pearson, 1975, Ong, 1983a). Above 25 °C the time of appearance of the first tiller does not change but there is a decline in the number of tillers (Begg and Burton, 1971; Ong, 1983a).

The rate of leaf production was accelerated at high temperatures (Pearson, 1975) although the number of leaf primordial on the main stem apex does not change from 18 to 30 °C (Theodorides and Pearson, 1981). The duration of the GS2 phase of development is very sensitive to temperature, averaging 18 days in length (McIntyre, et.al., 1993). Each one degree rise in temperature decreased the length of the period by about two days. There is also some evidence that the number of grains produced is determined during the GS2 stage and the amount of radiation intercepted during this phase is more important than the interception after anthesis (Ong, 1983b). This may be why the number of grains produced is inversely related to temperature from 22-31 °C since the duration of GS2 and therefore the amount of radiation absorbed is greatly reduced by increasing temperature.

Leaf extension is also important in controlling dry matter production. Ong (1983c) found a linear relationship between the rate of leaf extension and the temperature of the meristem. The more rapid the development of the leaves, the more rapidly the leaf area index (LAI) increases.

Reproductive stage GS3 Both the rate of spikelet production and the duration of the early reproductive phase were very sensitive to soil

temperatures since the meristem was at or close to the soil surface. Grain setting was optimum from 22-25 °C and declined at temperatures below and above this optimum while grain mass steadily declined with increasing temperatures from 19 °C to 31 °C (Ong, 1983b). Exposure of plants to prolonged periods of low temperature (< 13°C during the booting stage resulted in low grain set. High temperature during flowering results in a loss of pollen viability and can reduce the receptivity of stigmas and affect grain filling. This was due to lower temperature induced sterility of floret and pollen grains (Fussell et al., 1980; Mashingaidze and Muchena, 1982).

Daylength/Photoperiod:

Daylength, or photoperiod, is a critical control in the initiation of the reproductive phase of the millet in many pearl millet cultivars. Photosensitive cultivars are grown as long season crops while non-photoperiodic cultivars are grown as short season crops (The Syngenta Foundation for Sustainable Agriculture, 2003).

The two major millet growing zones of the world lie in different latitudes, 11 to 14 °N in West and Central Africa and between 25-30 °N in north-west India. In both these zones, the length of the growing season varies from 10 to 18 weeks in duration (Kowal and Kassam, 1978); Virmani et al., 1982). The length of the growing season is inversely related to the latitude and is more acute in West Africa, where season length changes markedly over a small region in latitude. Therefore, the roles of photoperiodic response differ in these regions. In West Africa, the onset of the rains is highly variable while the end of the rains is sharp (Kowal and Kassam, 1978). In such environments, photoperiodic control of flowering provides an opportunity to sow whenever the rains begin but ensures that flowering and grain filling occur when the moisture regime is most favorable (Mahalakshmi and Bidinger, 1985). This helps minimize grain mold, insect and bird damage that

affect early maturing varieties, and avoids incomplete grain filling of late maturing varieties due to any water shortages at the end of the season (Cocheme and Franquin, 1967; Kassam and Andrews, 1975).

Because of photoperiod sensitivity, the growth cycle of local millet cultivars changes greatly with sowing date. If sown in May or June, when days are long, the millet plant remains in the vegetative state (GS₁) until daylength reaches an inductive threshold. On the other hand, when sown in August or under shorter days, the duration of the vegetative phase is very short, with however, a minimum value that represents “intrinsic earliness” of ****the cultivar (Vaksmann and Traore, 1994). In addition, Kouressy et al., (1998) found that the number of leaves and the total biomass are higher with early sowing because of the extended development period. Bacci et.al.(1998) indicates however that this greater biomass yield is mainly due to stalks and not to grain yield. In other words higher biomass does not necessarily mean higher grain yields.

Solar Radiation

Solar radiation is an important asset in crop production. The amount of distribution of incoming radiation sets the limits for dry matter production. Radiation has two roles in crop production, namely the photosynthetically active radiation (PAR) for photosynthesis and the thermal conditions for physiological processes (World Meteorological Organization, 1996). Fortunately radiation is seldom a limiting factor in the tropics.

Pearl millet is a C₄ type plant, i.e., it has a high photosynthetic efficiency, particularly under high temperatures conditions because of reduced photorespiration (OMM, 1993). The efficiency of photosynthesis depends however on genotype, the age of the leaves and the degree of their exposure to direct sunlight. Direct sunlight is very important for both the morphogenetic processes of growth and the determinism of the flowering of pearl millet. Within the plant cover, the repartition of solar radiation involves leaf area density and plant architecture, also determined by leaf angle and planting

density (Begue, 1991). The fraction of the global radiation used for photosynthesis (PAR) has been suggested for the evaluation of pearl millet biomass, when water and nutrient supply is not limited (OMM, 1993). The following equation illustrates this relationship:

$$\text{Total Biomass} = \text{PAR}_a * E_c * t$$

where Biomass (m m^{-2}), PAR_a = absorbed photosynthetically active radiation, E_c = conversion efficiency of PAR into biomass (g MJ^{-1}), t = time.

The conversion efficacy of PAR (E_c), also called E_b (Birch et al., 1990; Sultan, 2002), is the slope of the linear relationship between accumulated dry biomass and absorbed or intercepted energy under optimal growing conditions.

With pearl millet, E_{ca} is not affected by daylength or crop density. Even temperature, when its values are above 21.5°C , does not affect E_{ca} despite its effect on growth cycle. However, high atmospheric water saturation deficit and/or lack of soil moisture can lower the radiation conversion efficiency because of stomatal closure triggered by these environmental conditions (OMM, 1993).

Radiation Use efficiency: Several studies have been conducted to determine the radiation use efficiency of pearl millet (McIntyre, et.al., 1993; Begue, A., et.al., 1991). Radiation use efficiency is defined as the dry matter production per unit of incoming solar energy. In a study in Niger (Beque, et.al., 1991) measurements of the components of radiative transfer were combined with measurements of biomass and leaf area index. A linear relationship was found between the photosynthetically active radiation (PAR) and the leaf area index (LAI). Pearl millet does have a relatively low LAI, reaching only 1.3 in this study. The conversion efficiency varies with the stage of development, being highest during tillering and then gradually declining as the crop matures (McIntyre et.al., 1993). Comparing irrigated vs.

non-irrigated responses to extreme temperatures and moisture stress, the radiation use efficiency did not change under varying temperature regimes when irrigation was applied. However the RUE of the non-irrigated plots did decline under extremely high temperatures.

Wind:

In West Africa, heavy winds associated with thunderstorms are common during the crop season. These winds are laden with dust particles that reduce the visibility and incoming amount and quality of radiation, and form deposits on leaf surfaces that may affect photosynthesis (WMO, 1996).

On the sandy soils in the southern Sahel, wind erosion owing to frequent sand storms, especially at the beginning of the rainy season, is one of the constraints to crop growth (Michels, K., et.al., 1993). If sufficiently buried, the “pockets” must be replanted. Surviving plants from partially covered pockets showed delays in growth and development. The maximum plant height and leaf number were lower with a significant reduction in the leaf area index. Grain yield from unaffected pockets were nearly twice that of pockets which were partially covered.

In shelterbelt studies in northern Nigeria, it was shown that *Eucalyptus camaldulensis* shelterbelts positively influenced yields of millets planted close to the belts. (Onyewotu et al., 1998). Experience showed that the shelterbelts would have to be no more than 100 m apart to fully exploit the protection of the crop from advected hot, dry air. Millet (this is not pearl millet) grown outside of the influence of the shelterbelts yielded about 50% less when including both methods of determining the onset of the growing season. Soil moisture availability early in the season and on its influence of growth, tillering and grain filling was the largest determinant in yield differences between plots. Substantial yield differences as a function of the distance from the belts could be explained by soil moisture at sowing and the effects of hot dry turbulent air generated by the belts on crop growth

conditions. The shelterbelts settled drifting sand and undulations and encouraged the return of soil protecting grasses. (Onyewotu et al., 2003)

A number of the factors which must be taken into consideration in the design and development of shelterbelts are described by Stigter (2005).

III. Management aspects of the crop in the various environments.

Traditional cropping systems in the Sahel are essentially a continuous pearl millet/cowpea intercrop grown at low plant populations with no chemical fertilizers and all production operations are done manually (World Bank, 1996). On the sandy soils of Africa pearl millet is typically planted either in a dry seedbed or immediately after the first rains. Rainfall can be sporadic, particularly early in the rainy season. However, because prolonged droughts can occur after sowing and during early the early seedling stages, growth can be greatly hindered. Since the total rainfall in these areas is still limited the timing of the early rains is very important for crop develop. Drought conditions, combined with high temperatures can be very detrimental to the emergence and development of the young seedlings. Strong winds can also cause damage the young seedlings and cover them with sand.

Land preparation/cultivation: In most cases, little or no tillage is done and weeding is started right after emergence in Africa. In sandier soils, the ground is dug over with a hoe and weeded prior to planting. Warm soils are required since higher temperatures encourage rapid germination (The Syngenta Foundation for Sustainable Agriculture, 2005). Millet is sown in hills, 10-15 cm deep, dug with a hand hoe, and weeding is carried out with a hoe that cuts the soil 2-5 cm under the surface. This not only cuts the roots of the weeds, but also breaks the surface crusts and facilitates water infiltration (De Rouw and Rajot, 2004). All these cultivation practices are common throughout the African Sahel where millet is grown on sandy soils.

In Pakistan the use of tractors for the preparation of the land is becoming more common, but bullock power is still important (Pakistan Agriculture

Research Council, 2006). The recommended practice is to plough the land twice immediately following harvest to bury the stubble and weeds and once or twice at sowing to prepare a fine seedbed. However, land preparation is usually inadequate, particularly in moisture-stress areas farmed by resource-poor farmers, where the land is usually ploughed only once. Also, even for those areas where tractors are available, the specialized implements needs for cultivation and harvesting have not been developed.

Because prolonged droughts can occur after sowing and during the early seedling stage, growth can be greatly hindered. Once the crop is established, there are a limited number of options available to the producer in the event of problems with insects and diseases.

Date of Sowing:

A major problem of rain-fed agriculture in semi-arid regions with short rainy seasons is how to determine the optimum sowing date. Traditional farmers have developed their own definitions, using accumulated experience and/or calendars based on local beliefs (Onyewotu et al., 1998). Some more scientific methodologies have been developed. For defining the onset date of annual rain in Nigeria, Kowal and Knabe (1972) used a combination of accumulated rainfall totals and rainfall/evapotranspiration relations as criteria. This was taken as “the first decade in the season in which the amount of rainfall is equal to or greater than 25 mm, but with a subsequent decade in which the amount of rainfall is at least equal to half the ET demand. Traditional farmers in parts of northern Nigeria define the onset of rains as “the day of the first good rain after the Muslim fasting period Ramadan, provided it was at least 7 months since the date of the last effective rain of the previous season (Onyewotu, 1996). Discussions with farmers participating in the study found that not all farmers have the same definition of the first good rain. Yields were significantly higher using a more scientific approach to determining sowing date. The overall differences in yield

between the two sowing dates must be mainly due to soil water availability, particularly during the seedling stage.

In Pakistan, millet fields in the rainfed “barani” areas, is sown with the start of the monsoon rains, usually during the first fortnight of July. In areas irrigated by hill torrents, the sowing period is usually from mid-July to mid-August, depending on the arrival of the flood water. In central Punjab irrigated millet (used primarily for fodder) is grown from May to July. In Sindh, millet for fodder may be grown from February to July, but for grain production, sowing is delayed to June-July to avoid flowering in July-August when the temperatures are extremely high (Pakistan Agriculture Research Council, 2006).

Fertility/Water Use Efficiency: The most common soil fertility management practice with pearl millet is fallowing. Sometimes, manuring is practiced either through corralling (the animals spend the nights on the field during the dry season) or spreading the manure across the fields (DeRouw and Rajot, 2004). The cultivation practices are the same on manured and fallowed land are common throughout the African Sahel where millet is grown on sandy soils.

Pearl millet responds well to additional plant nutrition. In a four year study in Oklahoma(USA) (Noble Foundation, 2006) to evaluate different summer forages, pearl millet was as productive on average as sorghum and sudan, but required five times less nitrogen (N) and was more efficient with the N it received. Increased fertility also results in an increase in water use efficiency. In a four year study at the ICRISAT Center in Niger, the increased yield due to the application of fertilizer was accompanied by an increase in the water use efficiency (WUE) in all four years. The beneficial effect of fertilizer could be attributed to the rapid early growth of leaves which can contribute to a reduction in the evaporative losses from the soil and increased WUE. (Sivakumar and Salaam, 1999) Over the four seasons, the average increase in WUE due to the addition of fertilizer was 84 percent.

Moisture conservation: Evaporation from the soil surface constitutes a large proportion of evapotranspiration of pearl millet fields in West Africa. Practical methods of reducing evaporation from soils to conserve water are lacking in West Africa (Payne, 1999). The use of organic mulch during the growing season would be a simple solution except that most of the crop residues are feed to livestock or used for building materials during the long dry season. Plastic mulch would also be effective, but such materials are too expensive or generally unavailable in most of West Africa.

Pearl millet leaf area indices are typically <0.5 during the early growth stages in semi-arid West Africa, causing transpiration to be a relatively small fraction of ET (Daamen, 1997). The probability of dry spells of ten days or more is high (Sivakumar, 1992), and crop water supply is often exhausted, necessitating resowing after the next sufficiently large rain event. Delayed sowing is generally associated with yield decline in pearl millet (Reddy and Vissar et al., 1993). Any reduction of evaporation (E) during this and subsequent periods would increase water supply for crop growth and reduce the risk of resowing.

The hilaire is a shallow cultivating, traditional hoe that has been used for centuries on sandy soils in West Africa to control weeds. It is pushed and then pulled by the user such that the blade cuts the roots of weeds 4 to 5 cm below the soil surface. The affected surface is pulverized and loosened. Furthermore, the color of the soil's surface becomes darker because the underlying soil layer has greater organic matter pigmentation. (Payne, 1999).

Hillel (1982) has suggested that one way to control evaporation during the first stage is to induce a temporarily higher evaporation rate so the soil surface is rapidly desiccated. This hastens the end of the first stage and uses the hysteresis effect to help arrest or retard subsequent flow. The use of the hilaire leaves the soil surface in a state close to what Hillel has proposed. In studies by Payne (1999) it was clearly demonstrated that ET was 45 mm less in tilled plots compared to untilled plots. In areas with 200-600 mm of

precipitation this represents from a significant reduction in moisture loss. However because of limitations in labor, it would be unrealistic to expect subsistence farmers to till entire fields with the hand-operated hilaire after each rain event. In order to render this technique useful to farmers, and animal drawn implement would need to be designed that reproduces the hilaire's effect.

A related issue is the practice of planting pearl millet in widely spaced rows. This is perceived to be a practice that reduces pearl millet crop failure. As a result, the leaf area index (LAI) in most fields seldom reaches 1.0. Even in more intensively managed fields, LAI seldom exceeds 2, and the period during which LAI exceeds this value constitutes only a small portion of the entire growth period (Payne, 2000). Payne (1997) found that increasing plant density from 5000 to 20000 "hills" ha⁻¹ increased yield and ET efficiency significantly even under low fertility even during 1984, the driest year on record. There appears to be no justification, at least in terms of crop water use, to the use of wide spacings. Canopy cover can also be increased by the introduction of an intercrop. In semiarid West Africa, pearl millet is most often intercropped with cowpea. Intercropping with cowpea has been reported to increase pearl millet grain yield by 15-103% in Mali.

Varieties: Although pearl millet in India is the crop of the rural poor in the harshest agricultural environments in India, F1 hybrid seed is used to sow over half of the 10 million ha on which this crop is grown because the potential yield obtainable from such hybrids more than pay for cost of the seed and other risks associated with hybrid-cultivation (Wisard Project Information 1999). The amount of money required to purchase the seed to sow an average holding is small (e.g., equivalent to L3 for seed to sow 1 ha of the most expensive commercial hybrid. Although pearl millet hybrids often give better grain yields than local open-pollinated cultivars, the genetically uniform single-cross hybrid cultivars currently available in India are more vulnerable to epidemics of pearl millet downy mildew. Such epidemics

constitute the major risk to cultivation of well-adapted pearl millet hybrids. Losses in individual fields can reach nearly 100%, and are estimated to average 14% across 10 million ha in India.

Intercropping: Intercropping, or planting two or more crops in the same field is one means of better utilizing limited resources. A study to quantify the use of resources in dominant millet-cowpea (M-C) and millet-sorghum-cowpea (M-S-C) intercropping systems was carried out by Oluwasemire, et.al. (2002) using standard farming practices under the low rainfall and poor nutrient supplies in the semi-arid zone of Nigeria. When intercropped, pearl millet used water more efficiently for grain production. It showed a better adaptation to moisture stress by producing similar harvest indices in sole and intercropped millet. The harvest index was defined as the ratio of the yield of grain to the total dry matter production of the plant. Millet was also the dominant crop in dry matter production when intercropped. This was due to the faster growth and higher tillering rates of millet, especially at low plant densities.

IV. Other background information on the crop

Drought tolerance mechanisms:

Deep Root Penetration: An important aspect of the ability of pearl millet to survive under high stress is its root system. Pearl millet roots can penetrate up to 180 cm deep, with approximately two-thirds of the root system in the top 45% of the soil zone (Mangat, et al., 1999). This deep root penetration may help millet species to exploit soil water more effectively and therefore overcome drought stress. Pearl millet root systems also have the ability to penetrate through hard clay pans in the lower soils. In addition, the photosynthetic rates were maintained through periods of severe drought (Zegada-Lizarazu and Iijima, 2004).

Pearl millet has a typical monocotyledonous type of root system consisting of a seminal or primary root, adventitious roots, and crown or collar roots (Mangat, et al., 1999). The seminal root develops directly from the radicle, adventitious roots from the nodes and the base of the stem, and crown roots from several lower nodes at or below the soil surface. The seminal root, an elongation of the radicle, is thin with a profuse fine lateral root system. These lateral roots develop within four days after radicle emergence and help in the initial establishment of the seedling. The seminal root is active up to 45-60 days after which it begins to deteriorate.

The adventitious roots start appearing 6 to 7 days after seedling emergence at the basal nodes of the stem. These grow rapidly and form a root system of secondary and tertiary roots which are the principle route of absorption of water and nutrients during the major part of the life cycle of the plant. Crown roots develop from the lower nodes near the soil surface approximately 30-40 days after seedling emergence. The crown roots above the soil surface thicken and support the plant, preventing it from lodging.

Leaf structure: Stomata are present on both leaf surfaces. The color of the leaves vary from light green to yellow to deep purple. The maximum leaf area (LAI) occurs at the time of 50% flowering, when the majority of the tillers have produced leaves. After flowering there is a decline in leaf area during which time the leaves begin senescing. At physiological maturity only the upper 3-4 leaves may be green on the main stem (Mangat et.al., 1999).

Stomatal sensitivity to evaporative demand is dependent upon leaf age and leaf area of the crop. This suggests that the degree to which water use is controlled by stomata and leaf area is influenced ontogeny so as to optimize crop water use for growth (Winkel et.al., 2001). It appears that stomates tend to remain open even under high levels of moisture stress. The implication is that millet does not tend to conserve moisture but rather transpires freely as long as the root system can supply the water it needs (Wallace, et.al., 1993). However, leaves will begin to senesce, thus reducing the LAI of the plant canopy. Stomatal regulation and leaf senescence are not

mutually exclusive; stomatal conductance decreases at leaf area increases. Conversely, a reduction in transpiring area increases stomatal conductance in the remaining leaves.

Diseases, pests and weeds:

Downy mildew, *Striga*, smut, ergot and rust are the major deterrents to pearl millet production, with the first 2 being by far the most important (The Syngenta Foundation for Sustainable Agriculture, 2005; World Meteorological Organization, 1996).

Downy mildew: Downy mildew (*Sclerospora graminicola*)(Sacc) constitutes the major disease risk to the successful cultivation of pearl millet (Wizard Project Information), particularly in India. In India, up to 30 percent of the harvest can be lost during years of severe attack, with losses in individual fields reaching nearly 100 percent (CGIAR, 2006).

Although pearl millet hybrids often give better grain yields than local open-pollinated cultivars, the genetically uniform single-cross hybrid cultivars currently available in India are more vulnerable to epidemics of pearl millet downy mildew. Such epidemics constitute the major risk to cultivation of well-adapted pearl millet hybrids

The primary source of inoculum for downy mildew disease are the soil-born sexual spores or oospores that can survive in soils for several years. Their thick cell walls protect protects them from desiccation and serves as an impermeable membrane. During cool and humid nights, the systemically infected leaves produce abundant sporangia on the abaxial surface. However, the hot and dry environmental conditions favourable for pearl millet growth may not be conducive for sporangial production and survival (Singh et al., 1993).

Three strategies have been identified to assist in the control of downy mildew in pearl millet: the use of disease resistant cultivars, seed treatment and/or early sowing..

In a recent study in Nigeria, the incidence of pearl millet downy mildew (DM), severity and yield losses of two pearl millet varieties (local and improved) due to the disease were determined in field studies (Zafari, et al., 2004). Significant reductions in the disease incidence and severity were recorded in plots sown with metalaxyl-treated seeds, indicating the efficacy of the fungicide. Metalaxyl protects seedlings for the first 20-30 days after sowing. Yield losses due to non-treatment of seeds was 40.88 and 45.39% in a local variety and 43.00 and 18.60 in an improved variety in the 2000 and 2001 cropping seasons.

A three-year study in Nigeria, Zafari (2005) studied the efficacy of combining sowing date, seed treatment with metalaxyl and the use of host plant resistance to control downy mildew in pearl millet. Early sowing gave lower disease incidence and higher grain yield than late sowing. The disease was controlled when metalaxyl treated seeds were sown early. The highest disease incidence and lowest grain yields were obtained when untreated seeds were sown late. Use of a resistant pearl millet cultivar along with seed treatment using metalaxyl greatly reduced disease incidence and increased grain yield in comparison with the seed treatment of susceptible cultivars.

Striga: *Striga* is a parasitic weed that creates major problems across much of Africa and parts of Asia. Twenty-one million hectares of cereals in Africa are estimated to be infested by *Striga*, leading to an estimated annual grain loss of 4.1 million t (Sauerborn, 1991). *Striga* is one of the major reasons that pearl millet productivity has remained at a subsistence level for so many years (IAPPS, 2007). *Striga* competes with the pearl millet plant for both water and nutrients. Consequently low soil fertility and low rainfall favor *Striga* infestations. *Striga* can be partially controlled by pre-treatment of seeds with herbicides which reduces or prevents the germination of the *Striga* seeds. New sources of genetic resistance have only recently been identified in the wild progenitor of pearl millet. It remains to be explored whether and how

these resistances can be transferred to farmer acceptable varieties (The Syngenta Foundation for Sustainable Agriculture, 2006).

Smut: Smut is a panicle disease (it attacks the flowering head of the pearl millet plant). The primary source of inoculum is spore balls in the soil from previously infected crop residue and surface contaminated seeds used for sowing (Thakur and King, 1988a). Moderate temperatures (25-30 °C) rather than cool temperatures, high relative humidity (>80 %) and long days seem to favour disease development (Kousik et al., 1988; Thakur, 1990).

Rusts: Rust is a foliar disease. Occurrence of the disease during the seedling stage can result in substantial losses in grain and fodder yield and quality. Cooler temperatures and high humidity favour disease development (Singh and King, 1991). When rust appears late in the season grain yield may not be affected, but the plant fodder is used as an animal feed after the grain is harvested. The disease causes a severe reduction of digestible dry matter yield of forage. Animal production could be improved by identifying rust resistance among popular and potential cultivars. In studies in 1997 and 1998 resistant varieties were identified. Of all the environmental parameters evaluated, only average temperatures below 27° C was consistently associated with the onset of rust epidemics.(Panwar and Wilson, 2001)

Insects and Pests

Pearl millet has relatively few menacing insect pest problems. In the Asia sub-continent, white grubs are the major pests (Rachie and Majumdar, 1980). In West Africa, there is a range of insect pests that damage the crop leading to economic losses but the major ones are the earhead caterpillar (Raghuval), stem borer (Acigonal), midge (Germyia penniset) and several species of grasshoppers.

White Grubs: The white grub (Holotrichia sp: Scarabidae) is an important subterranean pest that damages the root systems of several different crops,

including pearl millet. Based on the severity of the infestation, the crop is either harvested early or uprooted for the second crop. Some control can be achieved by the use of pesticides but they must be applied early in the season. The infestations do not become apparent until late August or early September when the grub attains its maximum size and becomes a voracious feeder (Parasharya et.al., 1994). The use of pesticides recommended as preventative measure against white grub must be applied at the time of sowing.

Earhead caterpillar (Raghuva): Pest surveys in West Africa indicate that crop devastated by these caterpillar infestations The number of surviving diapausing pupae in the soil emerge was associated with soil temperature and moisture at different depths from November to May. There is also a close relationship between moth emergence and the onset of rain and soil moisture was the key factor in diapause termination. The increase in soil moisture content and lowering of soil temperature in the upper soil layers was associated with earlier termination of diapausing pupae in this soil layer (Nwanze and Sivakumar, 1990).

Stem borer (*Acigona ignefusalis*): The time of the onset of rainfall and the total amount of rainfall during the crop season was related to the stem borer population (Nwanze, 1989). A knowledge of diapausing populations and the relationship between insect pests and rainfall during the season in regions where sporadic outbreaks is needed to integrate the weather parameters with the population dynamics of the pests.

V. User requirements for agrometeorological information

As indicated in other sections, to be of use the information provided must meet several important criteria. The information must be timely, it must be accurate, it must address specific needs, and must be in a form that it can be easily and accurately interpreted by the producer, extension service or whom ever is advising the producers.

The user requirements will vary greatly with the area where pearl millet is being grown. The largest pearl millet producing areas are located in the semi-arid tropics of Africa and India. As stated earlier a majority of those producers are subsistence farmers with very limited resources. The farms are small and usually cultivated by hand. On the other hand, other millet producing areas in mid-latitude areas involve more intensive production practices and are highly mechanized. The requirements for agro-meteorological information can be separated into three distinct time periods: current growing season; overall seasonal differences and longer term features of the climate.

Current growing season: With limited resources, both from a climate perspective and economic limitations, it is extremely important minimize risk and maximize the use of what is available. In the semi-arid tropical regions where pearl millet is grown, the initial establishment of the plant stand and the conservation of water are extremely important. Farmers want to avoid replanting a crop because of drought conditions or hot, dry winds immediately following planting and seedling emergence.

Choosing what to plant and where to plant is the main way farmers can respond to rainfall forecasts. Ingram et.al., (2002) have surveyed farmers in parts of west Africa to determine their awareness of seasonal forecasts and their interest in having that information. Farmers indicated that by itself a forecast of total season rainfall is of limited usefulness. Farmers in all sites stressed that precipitation forecasts must include estimates of duration and distribution of rainfall over time and space to be most valuable. In addition, most farmers requested that such forecasts be issued 1-2 months prior to the onset of the rainy season. This lead time enables them to optimize labor and land allocations, to obtain different varieties, and prepare fields in different locations.

In order of declining priority, the most salient rainfall parameters farmers want in are a forecast are: (1) timing of the onset and end of the rainy season; (2) the likelihood of water deficits occurring, that is, the like

distribution pattern over the growing season; and the total amount of rainfall. In the Sahel, information on seasonal rainfall quantities can help farmers to know whether to plant millet in high or low water retention areas.

To be understood and useful, forecasts need not only to provide relevant information at the optimal time, in the most appropriate form and language, and be delivered by credible sources. This task becomes even more challenging because farmers have different levels of access to formal education, availability of extension-type services and differences to adherence to local religious beliefs. This affects the extent to which local knowledge, including local climate forecasts remains a viable basis for farmer decisions.

The regional onset of the monsoon is very close to the ideal sowing date

Agro-meteorological information required to cope with climatic risks for any given season would include:

- Current climate regime and its affect on the onset of the rainy season, including the expected date of the onset of the rains. This could also aid in the medium term planting outlooks. Information on regional climate dynamics might help improve crop production locally. It has been shown the regional onset of the monsoon is very close to the ideal sowing date (Sultan, et.al., 2005);
- The development/adaptation of more scientific approaches to determine when sowing should begin;
- Timely information on the onset of the rainy season. Weather forecasts should including information on both temperatures and the likelihood of future precipitation;
- Expected conditions immediately after the rain onset. Wind and high temperatures are a common problem immediately following planting and seedling emergence.
- Date of the end of the rainy season;
- Development/adaptation of models for forecasting the developing of critical disease and insect outbreaks;

- Development of simple, practical methods of getting the appropriate information to farmers to help them maximize their limited resources.

Long Term Planning: Results suggest reduced African food production if the global climate changes towards more El Nino like conditions, as most climate models predict. Management measures include annual changes in crop selection and storage strategies in response to El Nino Southern Oscillation-based and North Atlantic Oscillation based predictions for the next growing season. It can also be important in the development of longer terms agricultural policy by regional, national governments and international organizations. The development of longer term policies must be based on baselines established by an analysis of historical conditions. From a climatic perspective the development of climatic atlases and associated analyses become extremely important.

Under the conditions where millet crops are cultivated, evaluation of rainfall in terms of probability estimates instead of arithmetic means is desirable, since, in most cases, rainfall becomes the key climatological element to determine the suitability of a locality for millet production.

The rainfall derived parameters such as the onset of rains, cessation of rains, duration of the rainy season, sowing rains, rainfall probabilities for specific phenological phases (sowing time, flowering, harvesting, etc). Rainfall probabilities can be estimated using the gamma distribution since it fits better than other mathematical distributions for rainfall data. (World Meteorological Organization, 1996).

Information required to cope with climatic risks for longer term planning would include the probability, frequency and timing of adverse weather conditions, including the distribution of rainfall, wind storms, beginning and ending of the rainy season;

The pattern of rainfall, temperature, evapotranspiration, relative humidity, sunshine hours, vapor pressure deficits and other agriculturally

significant climate variables (Uniganni 2002). Agroclimatological analyses of these significant variables for evaluating additional production areas, particularly in light of concern of potential changing climates.

Climatic risk zoning may be used to determine the best planting time to avoid or reduce drought effects on crop development. The following determinations/assessments are thus suggested for coping with climatic risk:

- n potential suitability of a specific variety for a given region
- n probability of drought at critical points in the growing season;
- n phenological stage most susceptible to drought;
- n availability of local meteorological data;
- n zoning of production districts based on climatic and edaphic conditions, and;
- n Information about the weather factors that are conducive to infestation by insects and infestation by pathogens to allow timeliness of control practices;
- n Suitable drought monitoring and characterization indices such as:
 - n water requirement index
 - n drought index
 - n available stored water
 - n probability of dry spells
 - n rainfall anomaly
 - n soil moisture holding characteristics

VI. Agrometeorological services including pearl millet in Africa and India.

Africa : Example 1

Sources: (Oluwasemire et al., 2002) and (Stigter et al., 2005).

The major cereals adapted to the rainfed region of the Nigerian Sudan savanna are pearl millet and sorghum. These cereals are predominantly intercropped with cowpea and/or groundnut. The most dominant crop mixtures are millet/cowpea, millet/sorghum/cowpea, millet/cowpea/

groundnut, sorghum/cowpea and sorghum/cowpea/groundnut. Cowpea has a dual purpose: the grain is used for human consumption and the remaining biomass as fodder for animals. Intercropping components adopted by farmers are grown at low densities, to minimise risks and exploit resources in a good cropping season. Experiments to determine improved answers that local intercropping systems can give to land degradation were conducted during 1994 and 1995 rainy seasons. It was found as an agrometeorological service with a view of improving the cereal/legume systems in the Nigerian arid and semi-arid zones that they should include genetically superior crop cultivars and the manipulation of the component densities along with the improvement of microclimatic variables. An amelioration of the cereal/legume intercropping systems may involve a reduction in plant density of the tillering and faster dry matter accumulating millet component, while the low growing and ground covering cowpea component density is increased. The results learn that abundant organic manure in combination with agrometeorological services on intercrop manipulation related microclimate improvements may control near surface land degradation in northern Nigeria under acceptable sustainable yields. Appropriate policy environments, in economics and research, must enhance this.

Africa: Example 2

Sources: (Onyewotu et al., 2003 ; 2004) and (Stigter et al., 2005).

This is about failures made in original attempts to protect millet crops in Sahelian Nigeria from advected heat by multiple shelterbelts. Farmers had to find for themselves that only close to the belts the crops were sufficiently protected. Only much later, participatory experiments demonstrated as an agrometeorological service why this was the case. At this same very late stage, while the farmers had long complained about allelopathy of the trees, was it shown that it did not exist and that root pruning and branch pruning did indeed away with all competition for resources between trees and millet. This showed the maximum benefits of the rehabilitation of the degraded land as

originally designed. Measures of soil and crop protection being insufficient, it resulted for the farmers of sheltered land in being economically worse off. The research learned that views held for now close to 20 years, that a soil management and rehabilitation policy must be formulated in the context of wider development objectives and a well-defined direction of social change, were confirmed. Although local adaptation strategies and contemporary science were jointly available, the policy environment was not conducive to useful information transfer, local initiatives and innovations. The answer to land degradation had initially been found in the establishment of the multiple shelterbelts. However, the answer of sufficient tree densities to prevent advected heat to spoil pre-sowing soil water conditions and unprotected millet crop growth was only found as an agrometeorological service by this research.

In India:

The Indian Meteorological Department recognized the importance of meteorology to increasing food production and established a Division of Agricultural Meteorology back in 1932. The Division has a wide network of agrometeorological observatories, which generate various kinds of data on agrometeorological parameters. In 1977, in collaboration with various state agricultural departments, the DAM began issuing weekly/bi-weekly Agromet Advisory Bulletins. The Advisory Bulletins contain specific agricultural advisories tailored to the needs of the farming community.

The primary aim of the service is to provide timely advice on the actual and expected weather and its potential impact on the various day-to-day farming operations. The advisories take into account the stage of the crops, agricultural operations in progress, prevalence of pests and diseases, and the immediate impact of weather on crops. They are prepared in collaboration with agricultural experts and broadcast over All India Radio (AIR). The bulletins contain specific advice for farmers for protecting their crops from adverse weather and to make the best use of prevailing favorable weather to increase production.

In addition to the Agromet Advisory Bulletins, the Farmers' Weather Bulletin (FWB) is also regularly issued from Regional Meteorological Centers. FWB's indicate the onset of rains, probable rainfall-intensity and duration, weak or a break in monsoon conditions, occurrence of frost, hail, squalls, and other conditions. The FWB are issued throughout the year in different regional languages. The bulletins are also published in newspapers.

India: Example 1:

Source: <http://www.indiaweatherwatch.org/agroad/Jodhpur.pdf>

**AGROMETEOROLOGICAL ADVISORY SERVICES
CENTRAL ARID ZONE RESEARCH INSTITUTE, JODHPUR**

Date: 16 March, 2007

Weather Forecast:

In the next 3 to 4 days (16th-19th March) Jodhpur and its surrounding 50 km area maximum and minimum temperatures rise by 3 to 4°C and clear sky conditions will prevail. Wind direction is expected northwest with 4 to 6 km/hr speed.

Agrometeorological Advisory:

Agrometeorological Advisory Services Committee of CAZRI suggested to farmers of Jodhpur region the following advisory.

1. Weather is favorable for harvesting the *rabi* crops. So farmers are advised to harvest the crop and put it safest place in field for threshing.
2. Farmers who have irrigation facility can grow fodder crops like fodder pearl millet and sorghum. For fodder pearl millet *Raj Chari*, *Rajaco Jayant*, *L-74* and for sorghum *Rajasthan Chari -3*, *Rajasthan Chari -3*, *Pusa Chri -6* and *M.P. Chri* are suggested for improved fodder. Seed rate should be used 12 kg/ha for pearl millet and 40 kg/ha for Sorghum. For improving the quality of the fodder crop should be mixed with 10 to 20 kg seed of cowpea and then sown. Before sowing seed should be treated by thirum 3 gm per kg seed.

India: Example 2:

Source: <http://www.hindu.com/2005/06/17/stories/2005061701491400.htm>

**Department of Agricultural Meteorology
Marathwada Agricultural University, Parbhani
Weather forecast and agricultural management
(For 04, 05, 06 and 07 August 2006)**

Bulletin No. 42 Date: 04-08-2006

Past weather condition: The skies remained mainly cloudy and a total of 18.6 mm rainfall was recorded during last four days .The maximum temperatures prevailed between 26.0 to 30.5°C, which were below normal by 0.0 to 4.0 °C. The minimum temperatures ranged between 20.5 to 22.5°C, which were below normal by 0.0 to 2.0 °C.

Total rainfall recorded from 1st June till to date is 255.4 mm as against normal 428.9 mm for the corresponding period.

Weather forecast: The skies are likely to remain complete overcast and a total of 110.0mm rainfall is expected during next four days as predicted by NCMRWF. The wind speed is likely to remain in between 8 to 9 kmph, which will be below normal by 1 to 2 kmph. The predominant wind direction will be 290 degrees. The maximum temperatures are likely to remain in between 24.5 to 26.5°C, which will be below normal by 4.4 to 6.4 °C. The minimum temperature will remain in between 20.0 to 21.0 °C, which will be below normal by 1.5 to 2.5.0 °C. There is a possibility of 140.0 mm cumulative rainfall during next 7 days.

Impact of weather on crops and Weather based Agro-advisories:

Farmers are advised to apply, 40kg, 30kg and 40kg/ ha N fertiliser to Sorghum, Pearl millet and Cotton crops respectively after cessation of rainfall.

Farmers are also advised to undertake plantation of fruit crops.

Infestation of leaf miner is noticed in soybean crop. For control of leaf miner, spraying of Dimethoate or monocrotophos 10ml in 10 liters of water is recommended.

Sd/-

Nodal Officer and Head

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