CHAPTER 13 G

AGROMETEOROLOGY AND SORGHUM PRODUCTION

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I. Introduction

Sorghum (Sorghum bicolor L. Moench) is a cereal grass, native to Sub-Saharan Africa and has been cultivated for centuries as a staple cereal grain (Menz et al., 2004). Other names for sorghum include Durra, Egyptian Millet, Feterita, Daza, Sorgo, Guinea Corn, Jowar, Juwar, Kaffircorn, Milo, Shallu and Sudan Grass. The many subspecies are gathered into four groups - grain sorghums (such as milo), grass sorghums (for pasture and hay), sweet sorghums (formerly called "Guinea corn" and used to produce sorghum syrups), and broom corn (for brooms and brushes). Sorghum was initially cultivated possibly around five thousand years ago and from that time man's continuous intervention has led to the development of the crop.

Sorghum is well-known for its capacity to tolerate conditions of limited moisture and be productive during periods of extended drought, circumstances that would impede production of most other grains. It has an extensive root system, waxy leaves and the ability to temporally stop growing in periods of drought, recovering when moisture becomes available again. This makes it an important crop in arid or semi-arid environments, where it may not be economic or productive to grow other cereals. It is an important food crop in Africa, Central America, and South Asia and in both total area planted and, production is the fifth most important cereal crop after wheat, rice, maize and barley, grown in the world, (FAO, 2006).

Although of tropical origin plant breeding has developed cultivars adapted to growth outside the tropics and as a result sorghum has been cultivated at latitudes from 45 degree north to 45 degrees south. In 2005 the area worldwide given over to sorghums was 44.7 million hectares which produced 58.6 million tonnes, an average of 1.3 t/ha. The USA produced 9.8 million tonnes followed by Nigeria with 8 million tonnes though the production was 4.3 t/h and 1.1 t/h respectively. Argentina, however, although producing much less sorghum than the USA, did so at 5.1 t/h. The main producer countries, respective harvest area and average yields are shown in the Table 1. About 90% of the area planted to sorghum lies in less developed countries, mainly in Africa and Asia, where it is grown generally for food by low-income farmers. The remaining 10% is made up of large-scale commercial farms, most of them in the developed world, which produce sorghum mainly for livestock feed. These farms account for more than 40% of global sorghum output.

Sorghum is among one of the most versatile species of plant. It is an important part of the diets of many people in the world, mainly those living in the drier areas of Africa and India (Datke et al., 2003). Besides its use as food for humans it is used as animal feed, as a raw material for the production of anhydrous alcohol, alcoholic drinks, glues, inks and biodegradable packaging materials. Sugar is also extracted from its stems. Sorghum is one of the best crops for silage because of its high yields (and being a C4 plant it is an efficient source of biomass) and the sugar content and juiciness of its stalk along with its adaptability to areas receiving too little rain to ensure crops of maize (Bakici and Demirel, 2004) lends it to this. The ensilage of sorghum also usually prevents stock losses from prussic acid poisoning.

Table 1: Main producer countries, harvest area and average yield of sorghum in 2005.

Country	Production	Area Harvest	Yield
	ton	Ha	t/ha
United States	9847680	2301470	4.279
Nigéria	8028000	7073000	1.135
Índia	8000000	9400000	0.851
México	6300000	1909090	3.300
Sudan	4228000	8000000	0.529
Argentina	2900000	558000	5.197
China	2592800	672600	3.855
Ethiopia	1800000	1350000	1.333
Austrália	1748000	659000	2.653
Brazil	1529600	758356	2.017
W O R L D	58620842	44703950	1.311

Source: FAO, 2006.

Physically the flowering panicles are used as brushes, brooms and whisks and the stems are used for weaving fences, mats, and in the building of wattle houses. In Africa the straw of the traditionally tall sorghums is used to make palisades in villages or around homesteads while the plant residues are an important source of fuel for cooking. The stems of wild varieties are used to make baskets and fish traps. Dye extracted from sorghum is used in West Africa to colour leather red.

Sorghum starch is manufactured in the U.S.A. by a wet-milling process similar to that used for corn starch from which dextrose is produced for use in foods. Starch from waxy sorghums is used in adhesives and for sizing paper and fabrics and is also an ingredient in oil drilling "mud". In the United States,

sorghum is a principal feed ingredient for both cattle and poultry. Its protein content is higher than corn and about equal to wheat. Its fat content is lower than corn but higher than wheat. Tannin, an acidic complex, can affect both the taste and nutritional value of sorghum though historically sorghum with high tannin content was only desirable because it was unpalatable to birds, a great pest of sorghum production. High tannin sorghum is still grown where birds represent production a problem. In the United States reduced-tannin sorghum has been developed improving its food use by as much as 30%.

Sorghum grains have a very similar structure to that of maize, although they are smaller and generally oval in shape. They both have a floury endosperm and a large fat-rich germ, but unlike barley or rice they lack a true hull (husk). Whole grains contain about 12% protein, 75% starch, 4% fat and 4% minerals. Sorghum has a very hard kernel, which makes it resistant to disease and physical damage but also makes it harder for animals to digest. To combat this it is ground, cracked, steam flaked, and/or roasted which enhances its nutritional value by 12- 14%.

II. Agroclimatology of the crop

The main factors that affect Sorghum production can be grouped into four general categories. Understanding how these affect production should increase both the plants survival and growth and its production efficiency. The main categories and factors are:

- **Climatic factors: rainfall (water management), solar radiation, photoperiod and temperature;**
- **Soil Factors: chemical and physical soil properties and topography;**
- **Crop management: fertilization strategy, plants arrangement, plants population, weeds and diseases control, etc.**
- **Genotype: potential of production, adaptability to the environment.**

<u>Rainfall – Water Management</u>

Of all the factors that affect agricultural production the deleterious effects of climate are the most difficult to ameliorate. Ally to this the variability and unpredictability of climatic and this becomes the main risk factor to production. Abiotic stresses such as drought or indeed excessive rainfall, very high or low temperatures, low insolation levels etc., can significantly reduce yields and restrict the latitudes and the soils where commercially important species can be cultivated. Of the climatic elements, water is the most important, its availability during the plants growth cycle generally being the single factor that limits crop yield, (Chiroma et al., 2006).

Water constitutes, in general, about 90% of a plants mass and is important for internal transport (minerals, photosynthates etc), temperature

regulation, as a milieu for biochemical reactions, as a solvent, as well affecting plant structure though pant turgor relationships.

The degree to which water deficit affects crop yield depends on the intensity and duration of the water deficit, the crop cultivar, the plant's development phase and interaction with any other yield determining factors. Water stress affects several plant growth aspects, including the anatomical, the morphological, physiological and the biochemical. Drought conditions can affect a plant's water and nutrients absorption, seed germination, opening and closing of stomata, photosynthetic activity, transpiration, enzymatic activity and several other metabolic and physiologic processes. However, the more obvious general effect with respect to water deficit is the reduction of plant size and mass, leaf area and seed yield.

Sorghum is well-known for its capacity to tolerate conditions of limited moisture and to crop during periods of extended drought in circumstances that would impede production in most other grain crops. It is one of the most drought-tolerant grain crops and is an excellent crop model for evaluating mechanisms of drought tolerance (Tuinstra et al., 1997). Sorghum is able to endure quite arid conditions through both drought resistance and drought escape mechanisms as a result of its extensive root system, waxy leaves and ability to temporarily stop growing when the drought becomes excessive. A drought escape mechanism is exhibited when sorghum becomes dormant under adverse water conditions but resumes growth when water relations improve even after relatively severe drought. Early drought stops growth before floral initiation and the plant remains vegetative but it will resume leaf and flower production when conditions become favorable again for growth. Late drought stops leaf development but not floral initiation.

For obtaining high yields, cultivars with cycle from 110 to 130 days require 450 - 650mm of water (Doorenbos and Kassam, 1979). In order to maximize sorghum yields soil moisture should be maintained above 55% of the available water capacity in the rooting zone of the soil profile throughout the growing season. When the growing period is long, stalking cultivars are capable of recovery by the formation of additional stalks with bearers, even if critical water deficits occur during vegetative growth. Extreme water deficits during the flowering period reduce pollination or cause spikes to dry out. The decrease of the resultant yield can be partially compensated by additional stalks with spikes (Doorenbos and Kassam, 1979).

In general the greatest water consumption coincides with the period in which the plants present the greatest height and leaf area index. Severe water deficits during this vegetative growth phase reduces the plants mass increase and leaf area development and consequently this affects the grain yield though the direct yield development phase that is susceptible to water stress is the reproductive period (flowering and seed filling). Cultivars used for the production of forage where green mass rather than grain yield is required do not present such defined critical periods and can just be allowed to respond to the water availability during the growing season. In this case, the water requirement is more a function of the leaf area development and evaporative demand of the atmosphere.

Photoperiodism

Of all of the environmental factors that plants respond to, photoperiod (day/night length) is probably the most important since this directly affects flowering. Photoperiodic control of flowering allows plants to co-ordinate their reproductive phase with their environment and with other members of their species (Childs et al., 1997). Most sorghums are sensitive to photoperiod and are classified as short day plants, in other words the night must be longer than a critical minimum. Photoperiod sensitive cultivars have a terminal vegetative bud that remains vegetative until days shorten enough to initiate its differentiation into a floral bud. This initiation happens at the critical photoperiod i.e. when the day length is short enough to initiate flowering but not long enough to prevent it. Genetically sorghums vary in their critical photoperiod. For example some tropical varieties have difficulty flowering in temperate regions where the day length is greater than 12 hours i.e. during the summer. On the other hand, photosensitive temperate varieties have a longer critical photoperiod of around 13, 5 hours (Magalhães and Durães, 2003) Some sorghum hybrids, however, are not photoperiod sensitive.

Temperature

Temperature is an important factor which affects sorghum growth and is directly related to solar radiation. The soil temperature affects the plants growth influencing root growth and metabolism, modifying the production of the growth promoters of the aerial parts and nutrient uptake. The germination and seedling establishment phase of sorghum growth is especially sensitive to cold temperatures and results in a reduced plant population and grain yield (Tiryaki and Andrews, 2001). Reduction of the soil temperature in the pollination and grain development periods reduces grain production. Adams and Thompson (1973) observed that grain production increased in the order of 10% when they covered the soil with clear plastic, which kept the soil temperature about 2 ºC higher during the growth period. Peacock (1982) and other researchers have suggested that the best temperature for germination is between 21 and 35 ºC and that 40 to 48 ºC have been lethal. Adams and Thompson (1973) also observed that when the soil temperature falls from 26 to 23 ºC in the pollination and grains formation phases, it provokes a fall in productivity. This was attributed to the negative influence of temperature on nutrient absorption and the translocation process.

Because of its tropical origins sorghum is very sensitive to low temperatures. Paul (1990) showed that for most sorghum cultivars a minimum temperature of 16 C was necessary for all physiological processes to occur. Low temperatures (< 10 ºC) cause reduction of the leaf area, stalking and plant height, decrease dry matter accumulation and delay the flowering possibly due to chlorophyll synthesis reduction and consequently photosynthesis. When compared to the corn, sorghum is more tolerant of high temperatures and less tolerant the low temperatures. When the average daily temperatures are lower than 20 ^{o}C, there is prolongation in the growth period from 10 to 20 days for each 0.5 ^{o}C of fall in temperature. High and low temperatures stimulate basal

stalking. Low and high temperatures (< 15 °C and > 35 °C) during the flowering and grain formation cause reduced yields.

In the development period of the panicle, around 30 days after germination, temperature affects the number of grains produced by the panicle. High temperatures during anthesis can cause flower and embryo abortion though floral development and fertilization can occur from 40 to 43 °C when the relative humidity is between 15 to 30%. High temperatures, 6 to 9 days after anthesis, reduce the seed weight. Low temperatures during anthesis affect panicle development, causing spike sterility through the affect on meiosis provoking pollen grain sterility. Both the intensity and duration of low temperatures are very important in influencing the extent of sterility. Peacock and Wilson (1984) show that the rate of leaf formation (leaves/day) increases when the temperature rises from 13 ºC to 23 ºC and then declines with temperatures over 34°C. Eastin et al. (1976) noted that night temperatures of 5 ºC above of the optimum reduced yield grains from 25% to 33%, and 10 ºC above the optimum reduced the yield by 50%. The phase most sensitive to temperatures above the optimum temperature is floral differentiation.

It is worth noting that the optimum values of temperature proposed for sorghum crop development are been contradictory. While most authors cite optimum values around 33-34 °C Norcio (1976) established the optimum temperature for sorghum development in field conditions to be between 35 and 42 ºC, although he emphasized that there are differences between genotypes. Peacock and Heinrich (1984) have found sorghum growing in the semi-arid tropics with air temperatures exceeding 40°C and soil temperature reaching values of 60 to 68 ºC. Soil temperatures of 18 ºC at 5-cm soil depth for three consecutive mornings are recommended for even, vigorous seedling emergence (Amathauer, 1997).

III. Other background information on the crop

Sorghum is a C4 plant (fixes carbon dioxide into 4 carbon acids) of tropical origin. It is productive (g/m2/wk) at high light intensities and high temperatures such those that occur in the tropics. It has high nutritional values for the various forms it is used in -- cut, pasturing, hay, silage or grains. It is considered an annual crop, although there are some varieties that can become perennial. It has a large number of varieties adapted to different climatic zones, including tempered (cold). The crop requirements are very similar to those of corn except it has a greater tolerance to drought. The development of sorghum in semi-arid regions indicates that this crop can resist drought and high temperatures better than corn so when the climatic conditions of a region are too hot and drought prone for corn sorghum becomes an excellent alternative. When established sorghum plants are very drought resistant and so they can succeed in arid soils.

The crop prefers a slightly to moderately acid soil though some cultivars will grow with a soil pH as high as 8. Plants are adapted to a wide range of soils varying from light loams to heavy clays though they thrive best on light, well

drained, easily worked soils of high fertility, with moderate to high water availability. Small amounts of alkali in sandy soils reduce a crops performance considerably though plants are moderately tolerant of saline soils. A basic dressing of NPK may be required for yield improvement and the crop usually responds well to additional dressings of nitrogen during growth. Rotation with a leguminous crop can provide a low-cost soil fertility increase. The effect of nitrogen deficiency on grain yield is greatest when it occurs early in the growing season. Low grain protein results when nitrogen deficiency occurs between anthesis and maturity.

During the plants first growth phase (planting until panicle initiation) rapid germination emergence and plant establishment is very important. Weed control when the plant is small and slow growing is important if reduced yields are to be avoided. Hybrids generally have faster root and leaf formation though in fodder sorghum varieties these are slower than in grain sorghums. If growth processes such as leaf area, root system development, dry matter accumulation and seed number potential are negatively affected in the phase from panicle initiation to flowering reduced yields will occur. The phase following flowering is a critical one as seed number is a very important grain yield component. In this third growth phase (flowering to physiological maturity) the factors considered important to yield are those related to seeds filling. The final yield is function of both the duration of seed filling and the rate of dry matter accumulation (Magalhães et al., 2003).

The height of mature plants can vary from 40cm to 400cm. Temperature, water deficit and soil nutrient status can affect the leaves expansion rate of leaves, leaf area duration and plant height though this effect is mainly seen in photoperiod sensitive genotypes. While the growth habit of sorghum is similar to that of maize it has more side shoots and a more extensively branched root system. The root system is very fibrous, and can extend to a depth of up to 1.5m although the plant extracts 75% of its water from the top meter of soil and because of this, in dry areas, the plant's production can be severely affected by the water status of the soil. Compacted soils or those with shallow topsoil can limit the plants ability to survive drought by limiting the plants root system development. Since these plants are physiologically suited for growing in hot dry areas it is essential that the soil has a well cultivated top soil and is kept from compacting to allow full exploitation of these characteristics. However, in acid soils and with high levels of aluminium the root system formation is reduced.

IV. Management aspects of the crop in the various environments

The crop productivity, when it is measured as dry matter production, depends on the difference between photosynthate accumulation from photosynthesis and photosynthate losses though respiration. Any factor that modifies photosynthesis and respiration can have effect both positive and negative in productivity. Such factors are light, temperature, water and nutrient availability.

Dry mass production is strongly dependent on the plant's leaf area up to panicle initiation. Although there are not many studies into the relationship between leaf development and temperature, it is known that if water and nutrients are adequate leaf development is highly dependent of the temperature. Peacock and Heinrich (1984) showed that the leaf emergence (leaves/day) increased when the temperature was raised from 13 to 23 ºC. It was also found that when the day and night temperatures went from 20/15 ºC to 35/30 ºC there was an increase of the leaf emergence. These authors also found that the leaf expansion increases up to 34 ºC above which leaf expansion rate starts to decrease. They also showed that below about 15 ºC leaf expansion ceases. Generally leaf expansion rate has been observed to be approximately 60cm^{2}plant^{-1}day^{-1}. The influence of temperature on the growth of roots has been little studied and the few existing results suggest that the growth temperature relation is similar the one for leaf expansion.

Knowing the maximum crop yield, technologies and/or management practices can be applied to try to approach or reach this figure. Appropriate crop management consists of practices which consider all the possible interactions that affect yield. However, there is no one set of practices which guarantee high yields. What is necessary, however, is a good knowledge of the crop and a sensible application of management practices which are targeted at the factors limiting crop yield.

Soil management practices that that have a positive yield effect should address the following:

- **to produce good soil drainage and water storage and so encourage root system development. Such practices may include no-tillage systems and crop rotation.**
- **to increase the soil depth available to roots and to enlarge the water extraction layer in the soil producing a larger soil water reservoir and consequently, greater, water availability to sustain the plants growth during short periods of drought.**
- **to raise or re-establish the soils nutritional level appropriate to the crop yield required.**
- **to use cultivars adapted to the region.**
- **to plan the sowing time to enable better utilization of solar radiation, prevailing temperatures and the water available for crop development with reference to any sensitive phase --- particularly important is water availability.**
- **to pay attention to pests and diseases that may reduce yield.**
- **to control weeds in order to reduce their competition for water, nutrients and light.**

In regions with irregular rain fall distribution and high evaporation to the atmosphere (characterized by high solar radiation levels, strong winds, elevated temperatures and low relative humidity of the air), the water availability in the soil, in the absence of irrigation, is fundamental to the success of agricultural productivity. Practices that lead to better soil structure and consequently a deeper plant root system contribute to increase the soil water availability to the plant. Chiroma et al (2006) observed that combining the practice of flat bed cultivation with mulching may eliminate the need for ridging in increasing the productivity of sorghum grain in semi-arid regions.

The no-tillage system (direct sowing) engenders better soil water storage conditions for growth and crop development and minimizes the adverse effects caused by small water deficits. The average soil pore diameter increases and this improves soil porosity and soil structure and increases the proportion of the soil water available to the plant. These factors, allied to the reduced soil evaporation and increase in water infiltration rate, allow larger water storage in no-tillage system soils compared to the conventional management systems involving soil disturbance. Organic matter, which occurs in relatively small proportions in most tropical soils, contributes to increase the soil specific heat value, improves the soils cationic change capacity besides performing the important function of soil matrix formation. Soil matrix greatly influences soil water retention and the supply of minerals to the plant. While greater water availability favours biomass formation it will also allow greater transpiration losses although the transpiration ratio (g water/g dry weight increase) for C4 plants such as sorghum is low.

Any crop management practices and as well as other factors should be adjusted to minimize any negative effects crop yield although, more importantly, they should to be altered allow maximization of the crop yield potential. However, any intervention in the crop production system should have an economic objective defined by pre-established criteria. Strictly, in practice, it is the economic criterion that, in the final analysis, dictates the crop management action.

Insect pests and diseases are important in sorghum production. In some regions, insects can be a major limiting factor in grain sorghum production. Commonly soil insects, stem borer, aphids, green bug and shoot fly affect the crop. Growers must be prepared to inspect the crop for insect pests and prevent injury from them (Buntin, 2005). Sorghum diseases such as seedling and foliage diseases, root and stalk rot, head blights and molds, can and do occur each year in several parts of the word. Diseases may cause leaf spots or leaf blights, wilts and premature death of plants. Sorghum diseases can cause harvest losses, affect the quality of the harvested crop and lead to losses in storage. Diseases of sorghum, like those of other crops, vary in severity from year to year and from one locality or even field to another. Such variations depend upon environment, causal organisms, and the host plant's resistance. To minimize losses due to sorghum diseases, it is important to correctly identify the disease or diseases present so that appropriate management steps can be taken (Bradley et al., 2007).

Appropriate crop management programs can minimize losses from insects and diseases and these include planting tolerant cultivars, rotate crop rotation, manage crop residues properly, timely harvesting, biological control and accurate and timely application of insecticides and fungicides.

Besides insects, birds are major pest that can reduce yield considerably. Several types of birds can infest grain sorghum during the period of hard dough to maturity, as they perch on panicles and eat the seed. Birds will consume whole seeds but also will break the seed leaving half of it on the panicle (Buntin, 2005). Hybrids with higher tannin content but also growing the crop in large field blocks may help to combat birds.

V. User requirements for climate information

Although the sowing time doesn't usually have any effect on the production cost, it affects the yield and thus the farmer's profit. Decisions affecting the sowing time should be based on the risk factors that can be minimized, as these represent efficient planning activities related to production. However, besides management practices Sorghum productivity is a function of several integrated plant factors e.g. interception of solar radiation by the canopy, respiratory activity, leaf photosynthesis (the source) and translocation of photosynthate to the grain (the sink).

The relative activities of the source and sink are functions of environmental conditions and plants try to adapt to conditions by balancing their activities. The different responses of genotypes to environmental variability, in other words to the iteration genotype x environment, means that both genotypic and environmental effects are not independent. Hence the importance of the sowing time is mainly with respect to the crop cycle i.e. through the relation of plant factors to the environment. For crop production this means trying to estimate the effect of environmental conditions on all plant growth phases. The great problem, however, concerns unpredictable environmental variations. Environmental factors such as precipitation, air temperature, wind speed, solar radiation, cloud cover etc can vary unexpectedly and vary spatially as well as temporally.

Climate and soil types are the variables that explain the regional differences causing water deficiency in the crops. Particular factors are available soil water capacity, rain distribution and amount and the evaporative demand of the atmosphere (Farias, 2004). In spite of being considered a crop tolerant to water stress, sorghum can suffer water deficit effects which reduce its productivity considerably. Therefore 'sowing time' refers to the period in which the crop has high probability of growing in both favorable soil and climatic conditions.

Although it is practically impossible to control the climate it is possible to define the season with best climatic conditions for sorghum development. For this, based on the climatic history of the region, some presuppositions should be established to evaluate the likelihood of successful cultivation and

thus define the best sorghum sowing time. Climatic considerations should include appropriate temperatures during all the crop growth periods, adequate photoperiod and a sufficient water supply, especially during plant development phases more sensitive to the water deficits.

VI. Examples of agrometeorological services related to this crop

With respect to this subject, the climatic risk zoning of sorghum developed in Brazil has been contributing to sowing times which present smaller climatic risk to the crop. In Brazil sorghum is generally cultivated in the summer after another crop and the sowing date depends on the growing season of the preceding crop as well as the sorghum growth cycle. Thus, for a definition of sowing time it is important to know and to quantify the risk factors and to try to establish the conditions to minimize them.

To establish the sorghum climatic risk zoning in Brazil the following were considered: the characteristics and distribution of precipitation, the available water capacity of the soils (resulting from the hydrological characteristics of the soil as well as the effective depth of the root system), the water consumption of sorghum in its different growth phases and cultivar's life cycle (Farias et al., 2003). With this base line information the risk was estimated for not attaining the crop water needs (expressed by the relationship between actual and maximum evapotranspiration) for each place and sowing time.

Figure 1, shows climatic risk maps in relation to sorghum in the Paraná State of Brazil. Such studies were carried out for the main regions of sorghum production and this information now constitutes an important tool for giving guidance for sowing date as well agricultural policies since the information can be used to establish subsidies, credit concessions and agricultural insurances. All the information for sorghum as well as for some others crops is available at www.agritempo.gov.br. Besides having information about climatic risk zoning, this web site also contains other important agro-meteorological information relevant to agricultural production in Brazil.

Besides the quantification of the water deficit risk occurrence and the characterization of the climatic conditions of a certain region this information allows areas to be defined which are subject to economic risk because of pests and diseases whose appearance is climatically related.

Many other agricultural practices such as soil management and soil preparation, weed control, harvest etc can be affected by climatic conditions and such practices benefit from the availability of climatic maps and forecasting.

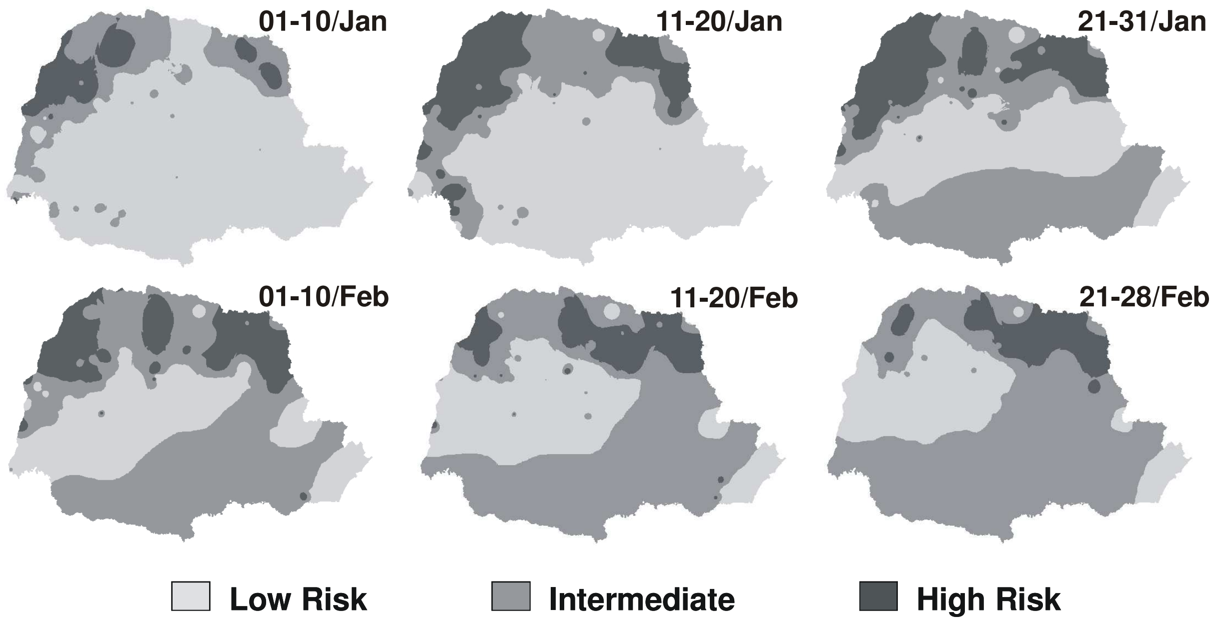

Figure 1: Climatic risk zoning to sorghum in the Paraná State, Brazil: water risk during six sowing periods, a cultivar cycle of 120 days and an available water capacity in the soil of 50mm.

Another example of agrometeorological services related to sorghum comes from Nigeria (Oluwasemire et al., 2002; Stigter et al., 2005). The hypothesis was tested, for the most abundantly occurring intercrops in semi-arid northern Nigeria, that these systems are generally more efficient in resource use under drier conditions than sole crops. This was done for dryland intercropping, with heterogeneous mixtures derived from patterns and varieties that farmers preferred, at low densities on-station. The most dominant crop mixtures are millet/cowpea, millet/sorghum/cowpea, millet/cowpea/ groundnut, sorghum/ cowpea and sorghum/cowpea/groundnut. The cereals are grown for consumption and cash. Intercropping components adopted by farmers are grown at low densities, to minimise risks and exploit resources in a good cropping season.

When the rainfall was below normal, the sorghum intercropping systems showed better water use efficiency than all sole crops. All the crops sown sole and intercropped rooted beyond 1m in the loose sandy soil. Sorghum root production was greater than for millet, while both cereals produced greater root densities than cowpea. Overlap of the roots of component crops suggests competition for resources. Cowpea produced greater root densities and achieved deeper rooting when intercropped with millet and/or sorghum than sole, suggesting adaptation and competitive ability under intercropping. Rooting depths of crops were shallower in a relatively wet season than when water was limiting. Root densities and proliferation of the cereals below the surface layer were much higher in low fertility soils than when nutrients were readily available. This is immediately useful knowledge as an agrometeorological service for designing such systems.

Another example of a sorghum related agrometeorological service to give here comes from Sudan (Ibrahim et al., 2000; 2002). In the Gezira irrigation scheme, serious symptoms of water waste have been identified in the last two decades with modern irrigation approaches with less field attendance, especially in sorghum and groundnut fields. A serious debate among authorities on return to traditional irrigation methods or other possible solutions needed quantification of the wastes concerned. On their request a quantitative study was undertaken to this end, that also should suggest ways to improve on the situation that are compatible with the local socio-economics of the use of sharecroppers. To possibly strengthen but at least verify the arguments of those who want to change the situation, it was thought useful to accurately quantify the problems under participatory on-farm conditions. Quantitative agrometeorology has sufficiently strong methods to be able to do so.

The study has revealed wastage of irrigation water in both irrigation methods but at different rates and also differently for each crop. The waste was higher in unattended irrigation of both sorghum and groundnut. Even much of the consumptive use is economically ill invested in non fertilized sorghum, because with higher inputs the same amounts of water would give higher returns. The application differences were mainly due to the watering methods, causing different amounts of standing water, and the methods of determining the moment of irrigation. Another type of non-productive water is the readily available water retained in the soil profile at the end of each growing season.

As an agrometeorological advisory it was stressed that more efficient water and farm management (e.g. weeding) in the scheme is crucial for obtaining the same or somewhat higher yields with other external inputs remaining at the present low level. The most important measure in this respect would be to adopt a land levelling program to the practical limits possible and to apply partly or fully attended watering on small areas, as was recommended in the traditional night storage system. Minimum practical standing water in the furrows during and immediately after each irrigation must be targeted. Economic measures related to the payment and prize of irrigation water should also be taken.

A final example of an agrometeorological service related to sorghum also comes from Sudan (Abdalla et al., 2000; 2002; Bakheit and Stigter, 2004). In the central clay plain of the Sudan, traditional subsistence farmers and small farmers that also produce for the local market want to keep the region near self-sufficiency. They combine annual production of sorghum with underground pit storage of part of the harvest. With increasing climate variability this food security is coming more and more under pressure. This encouraged farmers in Central Sudan to experiment with possible improvements of their traditional underground storage pits (matmuras) for sorghum grain. These innovations were quantified as part of the agrometeorological service.

Microclimate measurements of grain moisture contents, grain temperatures and pit air carbon dioxide contents in experimental pits made it possible, as another part of the agrometeorological service, to test and improve their designs. Derived farmer innovations of using shallower pits (50 cm in the

experiments), applying chaff linings at bottom and sides of these shallow pits (of at least 25 cm before compression by the grain filling in the experiments), made safe storage possible during at least two consecutive bad rainy seasons. Wide above surface caps (1 m beyond the pit diameter all around in the experiments), to diminish chances of cracks leading water to the grain, were a necessary condition added by the research experience.

Improved matmura systems have the potential to increase farmers' food security and better their economic position. Our initiatives showed that farmers in the Jebelmuoya villages could benefit from improved matmuras. Calculations indicate that improved sorghum matmuras could increase returns by up to 45% even in the case of small-scale farmers and that the larger the matmura, the higher the benefits. A recent survey carried out in three villages in the area showed that farmers were aware of the advantages of developing the system. Forty percent of farmers questioned in the survey commended improved sorghum matmuras for their storage qualities and low cost. They particularly appreciated the reduced need for chemical protection and the security they provided against theft and fire.

VII. References

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