10.1 AGROMETEOROLOGY AND COTTON PRODUCTION

10.1.1 Importance of cotton in various climates

Cotton is the world’s most important fibre crop and the second most important oilseed crop. The primary product of the cotton plant has been the lint that covers the seeds within the seed pod, or boll. This lint has been utilized for thousands of years for clothing the people of ancient India, Asia, the Americas and Africa. Cotton fabrics have been found in excavations at Mohenjo-Daro in India and in pre-Inca cultures in the Americas (Hutchinson et al., 1947). Lint, the most important commercial product from the cotton plant, provides a source of high-quality fibre for the textile industry. Cotton seeds, the primary by-product of lint production, are an important source of oil for human consumption. They can also be turned into a high-protein meal that is used as livestock feed. The waste remaining after ginning is used for fertilizer, and the cellulose from the stalk can be used for products such as paper and cardboard.

Cotton is grown on every continent except Antarctica and in over 60 countries around the world. In many countries, cotton is one of the primary economic bases, providing employment and income for millions of people involved in its production, processing and marketing (United Nations, 2003). Worldwide, cotton production totalled 120.4 million bales (218.2 kg/bale) in the 2004/2005 marketing year, the largest output on record (FAS, 2005). It was produced on over 35 million hectares, primarily in 17 countries. China was the world’s leading producer of cotton in 2004/2005, with an estimated output of 29 million bales. The United States was second, with just over 23 million bales. It was followed by India, with 19 million bales, Pakistan, with about 11 million bales, and Brazil, with almost 6 million bales.

The recommended soil temperature at seed depth should be above 18°C to ensure healthy uniform stands (El-Zik, 1982; Oosterhuis, 2001). Soil temperatures below 20°C, however, when combined with moist conditions, can reduce root growth and promote disease organisms that can injure or kill the seedlings. Cotton requires a minimum daily air temperature of 15°C for germination, 21°C–27°C for vegetative growth and 27°C–32°C during the fruiting period. Current commercial cultivars generally need more than 150 days above 15°C to produce a crop. They become inactive at temperatures below 15°C and are killed by freezing temperatures (Waddle, 1984). Mauney (1986) states that all processes leading to square, blossom and boll initiation and maturation are temperature-dependent. Cool nights are beneficial during the fruiting period, but extremes in temperature (low or high) can result in delayed growth and aborted fruiting sites. Gipson and Joham (1967, 1968, 1969) show that suboptimum temperatures retard growth and fibre development.

At least 500 mm of water (rainfall and/or irrigation) is required to produce a cotton crop. For water not to be a limiting factor in terms of yield, cotton needs between 550 mm and 950 mm during the season in a consistent and regular pattern (FAO, 1984). Untimely rainfall and/or irrigation, as well as humid weather during later stages of cotton growth, primarily once the bolls begin to open, may complicate defoliation, reduce yield and quality, lower the crop’s ginning properties (Freeland et al., 2004; Williford, 1992), or promote the attack of insect pests and disease organisms, such as boll rot (Boyd et al., 2004). Once the boll has opened, exposure of cotton lint to the environment causes weathering and the fibres can become stained, spotted, dark and dull. Parvin et al. (2005) state that yield is reduced by 10.10 kg of lint per hectare per centimetre of accumulated rainfall during harvest. The research of Williford et al. (1995) also measured a reduction in lint yield and grade for each successive rain event at harvest. Hence, the combination of warm, dry weather conditions, abundant sunshine and sufficient soil moisture from when the bolls start opening through harvest will maximize yield and quality potential. Figure 10.1.1 provides an example of the optimum climate needs for cotton.

10.1.2 Agroclimatology of cotton production

Adequate soil temperature and moisture conditions at planting are necessary to ensure proper seed germination and crop emergence (Table 10.1.1).
Table 10.1.1. Optimum climate needs for cotton

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Average daily temperature °Celsius&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average daily temperature °Fahrenheit&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Daily crop water use (mm)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Daily crop water use (in)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting (soil)</td>
<td>18° Minimum</td>
<td>65° Minimum</td>
<td>&gt;0</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Planting (air)</td>
<td>&gt;21°</td>
<td>&gt;70°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetative growth</td>
<td>21°–27°</td>
<td>70°–80°</td>
<td>1–2</td>
<td>0.04–0.08</td>
</tr>
<tr>
<td>First square</td>
<td>2–4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reproductive growth</td>
<td>27°–32°</td>
<td>80°–90°</td>
<td>3–8</td>
<td>0.12–0.31</td>
</tr>
<tr>
<td>Peak bloom</td>
<td>8</td>
<td></td>
<td></td>
<td>0.31</td>
</tr>
<tr>
<td>First open boll</td>
<td>8–4</td>
<td></td>
<td></td>
<td>0.31–0.16</td>
</tr>
<tr>
<td>Maturation</td>
<td>21°–32°</td>
<td>70°–90°</td>
<td>4</td>
<td>0.16</td>
</tr>
</tbody>
</table>

<sup>a</sup> Derived from listed sources.

Figure 10.1.1. Graph of optimum climate needs for cotton over the course of seven months. (Months are applicable to a crop in the southern hemisphere, and days from sowing will differ based on heat unit accumulation for each location.) (From ICT International (1998), Abdulmumin and Misari (1990), Deltapine Seed (1998), Erie et al. (1981) and Hake et al. (1996)
Photosynthesis is the driving process in determining production potential. Under optimum conditions in controlled, naturally lit plant growth chambers, a research cotton crop produced a yield equivalent to nine bales per acre, approximately three times the yield of commercially grown cotton under good field production practices (Reddy et al., 1998). Lint yield is generally reduced as a result of reduced boll production, primarily because there are fewer fruiting sites producing bolls, but also because of increased fruit abscissions due to various environmental stresses (Grimes and Yamada, 1982; McMichael and Hesketh, 1982; Turner et al., 1986; Gerik et al., 1996; Pettigrew, 2004a). Environmental conditions such as overcast skies, rainy weather, water deficits and high temperatures (day and/or night) will decrease photosynthesis and the supply of photosynthate. The decreased supply of photosynthate increases square and boll shed, and thus reduces the total possible number of harvestable bolls. Plants with the highest boll load are the most sensitive to low light intensity due to their increased photosynthate requirements of (Guinn, 1998).

Water stress caused by a deficiency of water manifests its damage as reductions in photosynthetic activity and increases in leaf senescence (Constable and Rawson, 1980; Krieg, 1981; Marani et al., 1985; Faver et al., 1996). Drought stress causes severe shedding of small squares, resulting in a decrease in flowering. Water stress during the first 14 days after anthesis also leads to boll abscission, but large squares/bolls do not shed readily and flowers seldom shed. Therefore, even under severe stress, young plants can often continue to flower. Water stress from 20 to 30 days after anthesis results in smaller bolls and reduced seed weights (Guinn, 1998). Moisture deficit stress reduces plant growth, resulting in stunted plants with reduced leaf area expansion (Turner et al., 1986; Ball et al., 1994; Gerik et al., 1996; Pettigrew, 2004b). Water deficits can reduce fibre length when the stress is severe and occurs shortly after flowering (Bennett et al., 1967; Eaton and Ergle, 1952, 1954; Marani and Amirav, 1971; Pettigrew, 2004a). Drought stress can also reduce (Eaton and Ergle, 1952; Marani and Amirav, 1971; Pettigrew, 2004a; Ramey, 1986) or increase (McWilliams, 2003; Bradow and Davidsonis, 2000) fibre micronaire depending on when it occurs. If the drought is severe late in the season, with the result that set bolls do not have the assimilates necessary for their full development, micronaire will be reduced. If the stress is during peak bloom, a reduced number of bolls will be set; if this is followed by rain later in the season, assimilates will be readily available for the reduced boll load, resulting in increased average micronaire of the field.

Water stress often occurs concurrently with excessively high afternoon temperatures. Reddy et al. (1991, 1992, 1999) demonstrate the detrimental effect that temperatures outside of an optimal range can have on a cotton plant and its fibre growth and development in closed environmental plant growth chambers. Cotton has the ability to mitigate exposure to high temperatures by evaporative cooling of the leaves via transpiration. High humidity, however, has a negative impact on the plant in certain growing regions, such as that found in the Mississippi Delta, and the response to irrigation can be affected by reduced evaporative cooling efficiency of the plant. This higher humidity reduces the level of evaporative cooling, making the plant more susceptible to heat stress at lower air temperature.

Cotton lint yields and fibre quality are also affected by the amount and quality of the solar radiation. Given adequate water and insect control, cotton grown under arid conditions such as those found in Australia, the Middle East and the south-western United States can routinely produce lint yields in excess of 3 to 4 bales per acre with the abundance of sunlight in each region. In humid areas in the south-eastern United States, however, where clouds can be much more prevalent, lint production is limited by the amount of sunlight received (Eaton and Ergle, 1954; Pettigrew, 1994). The lint yield reduction resulting from low light situations is primarily due to a decline in the number of bolls produced by the plants (Pettigrew, 1994). Not only is lint production reduced under low light conditions, but the fibre produced is often of inferior quality. Both Pettigrew (1995, 2001) and Eaton and Ergle (1954) found that shade treatments or reduced light conditions produced weaker fibre with a lower fibre micronaire. These fibre quality reductions were associated with alterations in various fibre carbohydrate levels, which are indicative of a reduction in the level of photoassimilates produced (Pettigrew, 2001).

Wind can also stress the cotton plant enough to reduce yield, although some wind may be beneficial in very hot and humid conditions. Wind modifies the temperature and humidity gradients around the cotton plant, which in turn changes the evaporative demand. Most wind damage to cotton plants occurs during the first 3 to 6 weeks after emergence, when the wind picks up soil particles and damages the young seedlings during impact. High winds can cause blowing sand that is capable of literally cutting the young plants off at the soil surface (Barker et al., 1985a, 1985b), thereby reducing the overall stand. In regions such as the Texas High Plains, where the winds blow hard and constantly, management practices that provide
protection for cotton plants are designed to improve plant growth and yield. Strip cropping, where taller crops are planted around the cotton seedlings, offers benefits related to the maintenance of soil moisture. Standing wheat and other stubble can also offer protection to the early seedlings (Barker et al., 1985a, 1985b). Extreme wind damage can sometimes occur in mature cotton crops, as was evident in 2005 when Hurricanes Katrina and Rita ravaged parts of the cotton crop in the Mid-South United States (JAWF, 2005a, 2005b). Immature bolls were beaten off of the plants and seed-cotton was blown out of mature open bolls. Leaves of the non-mature plants were stripped in locations where the strongest winds occurred.

Environmental factors have an impact on the growth not only of the cotton plant, but also that of pests and beneficial organisms. Both undesirable and beneficial plant and animal species are altered by factors that affect the crop, and should be considered during the growing season. Some climate regimes are unsuitable for beneficial plants, such as rotation crops or winter cover, as well as beneficial insect survival. On the other hand, weather patterns can encourage the growth of some pest insects and allow their populations to expand to a level that may damage crops. In areas that are not subject to freezing temperatures during the winter, disease and insect pests can over-winter and have a detrimental effect on young cotton. Knowledge of these interactions is essential when attempting to maximize cotton yields.

10.1.3 Other background information on cotton

The cotton plant is a deciduous, indeterminate perennial plant in the genus *Gossypium* of the family Malvaceae, or mallow family, and is native to subtropical climates. Two Old World diploid (2n = 2x = 26) species, *G. arboreum* and *G. herbaceum*, and two New World tetraploid (2n = 4x = 52) species, *G. barbadense* and *G. hirsutum*, have been domesticated independently for cultivation throughout the world. The most widely grown species worldwide is *G. hirsutum*, which is grown on over 95 per cent of the worldwide cotton hectarage, followed by *G. barbadense*. Upland cotton, *G. hirsutum*, is native to Mexico and parts of Central America; pima, Egyptian or American-Egyptian cotton, *G. barbadense*, is native to South America (Brubaker et al., 1999). India is an exception to most countries, with only 30 per cent of its cotton production area planted to *G. hirsutum*, 17 per cent planted to *G. arboreum*, 8 per cent to *G. herbaceum*, and the remaining area planted to interspecific and intra-specific hybrids.

Cotton is cultivated as an annual shrub in the temperate and even subtropical zones, and it develops in an orderly, predictable pattern. Plant development in cotton proceeds through five growth stages: germination and emergence, seedling establishment, leaf area canopy development, flowering and boll development, and maturation. Marur and Ruano (2001) define the growth process in four phenological phases: vegetative, squaring, flowering and boll opening. The seed contains two well-developed cotyledons, a radicle, a hypocotyl and a poorly developed epicotyl. The cotyledons will form as the seed leaves that provide energy for the developing seedling and are photosynthetically active during early seedling development. Moisture from the surrounding soil is imbibed into the seed through the chalaza, an area of specialized cells at the broad end of the seed. The water follows the tissue around the embryo to the radicle cap at the narrow end of the seed. The seed/embryo swells as water is absorbed, causing the seed coat to split. Under favourable conditions, the radicle emerges through the pointed micropylar end of the seed in two to three days, becoming the primary root that grows downward into the soil. The hypocotyl grows rapidly and elongates, arching near the cotyledons. The cotyledons are located at the lowest node on opposite sides of the stem. As the hypocotyl becomes longer, the cotyledons and the epicotyl are pulled/pushed through and above the soil surface. Exposed to light, the cotyledons unfold, expand, turn green and begin to manufacture food.

Much of the early growth of the cotton plant is focused on the development of a substantial root system. The primary root, or taproot, penetrates the soil rapidly and may reach a depth of up to 250 mm by the time the cotyledons expand. Root development may proceed at the rate of 12.5 to 50 mm per day, depending on conditions, so the roots may be 1 m deep by the time the plant is only 305 mm tall (Oosterhuis and Jernstedt, 1999). The taproot continues to elongate until the plant is at maximum height soon after flowering. The bud above the cotyledon enlarges and unfolds to form the stem where true leaves and branches will develop. A fully developed cotton plant has a prominent, erect main stem consisting of a series of nodes and internodes. As the plant grows, the internode above the cotyledons extends, and a new node is formed, from which the first true leaf unfolds. This process continues at 2.5- to 3.5-day intervals. A single leaf forms at each node in a spiral arrangement. At the centre of this growth activity is the terminal bud. The terminal bud controls the upward pattern of stem, leaf and branch development. About four to
five weeks after planting, vegetative and reproductive branches begin to form between the leaf petiole and the main stem node (Oosterhuis and Jernstedt, 1999).

Under optimal conditions, flower buds can be seen five to eight weeks after planting, as small, green, triangular structures commonly or colloquially know as squares. The first square is formed on the lowest reproductive branch of the plant located at the fifth to ninth main stem node. New squares will continue to appear on the next reproductive branch up to the top of the plant every 2.5 to 3.5 days and will appear outwardly along each fruiting branch at approximately five- to six-day intervals. The research by Bednarz and Nichols (2005) on selected modern cultivars shows a horizontal fruiting interval of 3.2 to 4.4 days. The total time from plant emergence to the appearance of the first flower bud is about six weeks. Each flower bud develops into a bloom about three weeks from the time it is visible to the unaided eye.

The cotton bloom is a perfect flower with white petals on the day of anthesis. The ovary has 3 to 5 carpels or locules. Each locule contains 8 to 12 ovules that may develop into seed. Flowers open during the morning, and pollination occurs within a few hours. Fertilization takes place within 24 to 30 hours after pollination and the fertilized ovule develops into seed (Oosterhuis and Jernstedt, 1999). The white petals of the flower turn pink after 24 hours and die the following day, usually shedding from the developing boll within a week. The growth rate of a boll is temperature-dependent and a boll will reach its maximum volume in about 24 to 30 days after anthesis. After anthesis, approximately 50 days are necessary for the fibres inside the boll to mature and the boll to open.

Cotton fibres are formed from individual cells located on the seed epidermis. While firmly attached to the seed coat, the fibre elongates for 20 to 25 days after fertilization and then grows in diameter for another 20 to 25 days. The developing cotton fibre is like a hollow tube, with successive layers of cellulose deposited on the inner surface of the fibre wall in a spiral fashion. The amount of cellulose deposited determines the fibre strength, fineness and maturity. Micronaire, a measurement of both fibre maturity and fineness, can be more heavily influenced by the environment than other fibre traits. High temperatures or drought during the elongation phase of fibre development can shorten fibre length and reduce fibre uniformity, and can cause high, or even under extreme conditions, low micronaire (Ramey, 1999). Cotton lint is creamy white to white when the boll opens. Fibre quality is at its maximum as soon as the boll opens, and declines thereafter until harvest due to environmental interactions.

10.1.4 Management aspects of cotton production

There are various management practices that should be followed to help mitigate some of the environmental risks associated with growing cotton. They include selection of adapted cultivars, planting within the recommended range of favourable planting dates and environmental conditions, use of seed and seedling protectants to avoid stress or early-season diseases and insects, use of effective pest management tactics to avoid competition and damage by weeds and insects, management for optimal soil moisture, proper fertility management, and management for maturity and readiness for harvest at optimum times. There is an abundance of university extension service recommendations and other government agency sources of information to assist a cotton grower in making good management decisions to avoid or minimize risk. These sources include environmental and climatological monitoring and forecasting services. Some risks will never be avoided unless the cotton is grown in a protected, controlled environment, such as growth chambers or greenhouses; this approach is not economical for commercially grown cotton at this time, however.

One of the tools used in reducing environmental risks and increasing the possibilities of a profitable yield is cultivar development through breeding and genetics. Successful cultivar development incorporates risk aversion into the genetic code of adapted varieties. Traditional breeding methods are used with aggressive selection pressure to develop genotypes with favourable traits for environments of interest. New cultivars are selected in the breeding programmes based on their yield, fibre quality and other desirable traits. The selection process ensures that new cultivars are developed within the current climate cycle or pattern and therefore have those recent environmental risks built into their genetics. When a new cultivar is released for commercial production, its primary selling point is its high and consistent yield. Producers are primarily paid for their crop based on yield, and therefore should choose to plant cultivars based on their yield history over the past few years in the given locality. One needs to remember that genotypes bred in one location or environment may not be the ideal cultivar for another location or environment.

Breeding also allows for traits to be bred into a genotype, or cultivar. For example, as reported above,
extreme heat results in delayed growth and loss of squares and fruit. Heat tolerance can be genetically manipulated in cotton. Certain cultivars have been identified that perform better under hot temperatures. Therefore, breeders have been successful in selecting for these traits and in developing heat-tolerant (Feaster, 1985; Lu et al., 1997) and drought-tolerant lines (Basal et al., 2005). For example, higher-yielding pima lines have been developed by selecting for increased stomatal conductance, thus allowing these lines to keep their leaves cooler (Radin et al., 1994; Percy et al., 1996). Salt tolerance is another inherited trait that cotton breeders have been successful in incorporating into new cultivars (Higbie et al., 2005). These cultivars will give growers greater success in increasing germination in salty soils. Cotton seeds with enhanced emergence force that break through soil crusts have also been selected by breeders (Bowman, 1999), with expectations that a higher percentage of the seedlings will emerge to produce even and uniform plant stands.

One of the largest contributions breeding has made to current United States Mid-South cotton production has been the development of earlier-maturing cultivars. These cultivars were bred to better fit the climate of this area and to mature as much as 30 days earlier than historical cultivars. These cultivars take better advantage of the normal weather pattern of the area by being in the fruiting stage while there is still moisture available in the soil, starting the maturation process during the drier times of the summer and being harvestable prior to the normal rainy period of the late fall and winter. These cultivars have also been created to produce yield despite the intense pest pressures of the area. A secondary contribution breeding has made is the introduction of pest-tolerant traits into the cultivars. These cultivars can produce toxins or tolerate toxins in order to control specific pests that previously would reduce yield. These cultivars were bred in the Mid-South, so were selected based on their ability to adapt to that environment.

Weather conditions often determine the type of pests that will have to be controlled in a given growing season, as well as the efficacy of control procedures. Weed pests of cotton change according to regional climatic conditions, cultural practices and local weather variables. Herbicides often require actively growing plants to achieve good control. Moisture and temperature generally control how actively weeds grow. Plant pathogens and insect pests in most cases require alternate hosts. The alternate host’s growth is dictated by regional climatic differences and local weather variations. Insect pests, for example, move from the alternate hosts into cotton when that host is less attractive to the pest than cotton, mostly when the host is dying or senescing. Spider mites, for instance, generally require dry weather. The dry weather prevents beneficial fungi from producing an epizootic, thus eliminating the spider mite population. Effective pest control requires good timing to be beneficial, and one of the largest obstacles to properly timed crop protection applications is weather. If improperly timed, crop protection products may fail and the resulting uncontrolled pest population could damage the crop. Each crop protection product is active only within a certain environmental regime or during a certain life stage of a pest. Temperatures that are too high or too low, or rain prior to or after application, may cause failures. Moisture and/or high winds can prevent the timely application of products and thus reduce control and yield.

Following local extension recommendations or governmental guidelines will help reduce environmental risks to producers. These recommendations and guidelines usually include planting and harvesting dates that consider risks of temperature and precipitation extremes and other general environmental factors. They also may include timing suggestions for certain practices that would have adverse effects if done at alternate times. Soil sampling, which helps to identify many soil issues that could limit production, is one of the recommended tasks. Sampling is a tool that may be used to identify limiting nutrient, pH or salinity factors that can reduce yields and/or fibre quality.

Since freezing temperatures kill cotton plants, the crop has to be grown between the last spring and first fall freezes. Climatological records can identify the growing period for a location and they can be used to compute the statistical probability of a freeze occurring before or after certain dates. Growers must realize and take advantage of these data in order to reduce the risk of the crop’s being killed by freezing temperatures after planting in the spring, or prior to maturation in the fall. The National Climatic Data Center computed this dataset for many sites across the United States and the results are available for producers to utilize (Koss et al., 1988). The dataset provides three probability levels (10, 50 and 90 per cent) for the occurrence of a certain temperature (–2°C, 0°C and 2°C) after a certain spring date and before a certain fall date. Producers have to weigh those risks and decide whether or not to plant. Even though the current weather may be ideal for planting, producers should not plant if the likelihood that a freeze will occur after that date, expressed as a percentage, is higher than the risk they are willing to accept, also
expressed as a percentage. Producers should utilize this information to determine the last day they are willing to plant as well, since the crop has to have enough time to mature prior to the first fall freeze. Other information derived from climatological data is also beneficial to growers, such as the number of days a grower has to complete tillage and non-tillage operations during a season (Bolton et al., 1968; Zapata et al., 1997).

There are also certain cultural practices that may be utilized to reduce some of the environmental risks associated with growing a cotton crop. Seeding rates need to be sufficient to achieve an ideal plant population for all locations. Plant populations of 68,000 to 101,000 plants per hectare are recommended on bedded rows and populations of 197,000 to 247,000 plants per hectare are typical in the case of ultra-narrow row or broadcast cotton production. When planting, seed depth is critical and seeds should be placed at 10 to 25 mm, depending on soil type, crusting potential and moisture levels. If planting immediately precedes a rain, certain soils will crust and seal over, depriving the seedling of oxygen that is required for germination and root development, and making it more difficult for the seed to push through the soil for emergence. Planting seed at the shallower depth is recommended under these conditions to improve emergence (Delta Agricultural Digest, 2006). Even planting seed at greater depths, up to 30 mm, is not uncommon when planting to the moisture level in the soil in arid and dry areas. This, however, is not the ideal situation, as more seed may have to be planted to achieve the desired final plant stand. Strip cropping and interplanting may be utilized to reduce wind effects on seedlings. Skip-row planting may be used for better soil water utilization and a higher field-level drought tolerance.

The most obvious and beneficial cultural practice that can be utilized to reduce environmental risks is irrigation. Supplemental irrigation should be applied if needed during dry periods. Field drainage is also very important, as cotton cannot remain in saturated soil. Any practice that can improve the surface or subsurface drainage is very beneficial. Tillage operations such as bedding or subsoiling, or inserting drainage tiles, may be utilized to improve field drainage.

10.1.5 User requirements for agrometeorological information in cotton production

User requirements for agrometeorological information will vary depending on the climate, cultivar and soil type of the region where the crop is grown. Commercial cotton production worldwide is in a constant battle to keep the cotton plant unstressed so that it is able to retain its fruit, while environmental factors are constantly stressing the plant, and certain requirements need to be followed in all locations. Current cultivars require between 1,195 and 1,275 degree-day (DD15.5°C) heat units based on 15.5°C from planting to harvest to produce an acceptable yield (Delta Agricultural Digest, 2006). The degree-day baseline is derived from a very large pool of research that studied temperature effects on different growth stages (Mauney, 1986; Anderson, 1971; Young et al., 1980; Bilbro, 1975). Recent research has shown that a higher baseline temperature, combined with other weather variables, may better predict boll maturation (Viator et al., 2005). Degree-day heat units are calculated by taking the daily average temperature, (Max + Min)/2, and subtracting the base, either 15.5 for Celsius or 60 for Fahrenheit, from the daily average. The resulting number is the number of heat units accumulated for that day. High-yielding cotton also requires between 508 and 1,016 mm of water during the growing season. If a location normally has little or no precipitation during the growing season, irrigation is necessary. Cotton also requires a soil with excellent water-holding capacity, aeration and good drainage, since excessive moisture and waterlogging are detrimental to production.

During germination, the soil must have reached a minimum soil temperature of 18°C and have moisture available, but not be saturated. Soil temperatures

### Table 10.1.2. Growth stages indicated by accumulation of degree-day heat units
(Compiled from Delta Agricultural Digest, 2006; Boyd et al., 2004; Kerby et al., 1987; Young et al., 1980)

<table>
<thead>
<tr>
<th>Stage</th>
<th>DD15.5°C</th>
<th>DD60°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>From planting to emergence</td>
<td>25–35</td>
<td>50–60</td>
</tr>
<tr>
<td>From emergence to first fruiting branch</td>
<td>165–190</td>
<td>300–340</td>
</tr>
<tr>
<td>From emergence to first square</td>
<td>235–265</td>
<td>425–475</td>
</tr>
<tr>
<td>From square to white bloom</td>
<td>165–195</td>
<td>300–350</td>
</tr>
<tr>
<td>From emergence to peak bloom</td>
<td>770–795</td>
<td>1,385–1,435</td>
</tr>
<tr>
<td>From white bloom to open boll</td>
<td>415–610</td>
<td>750–1,100</td>
</tr>
<tr>
<td>From emergence to a mature crop</td>
<td>1,165–1,250</td>
<td>2,100–2,250</td>
</tr>
</tbody>
</table>
below 20°C reduce root growth and when combined with moist conditions promote disease organisms that can injure or kill the seedlings. Forecast daily average temperatures should be above 21°C for the five days immediately following planting in order to assist in quick germination and the establishment of a healthy plant stand. These requirements increase the possibility of growing a good radicle. Damage to the radicle at this point will cause a shallow root system, leaving the plants more susceptible to water and drought stresses (El-Zik, 1982; Oosterhuis, 2001).

After planting, optimum daily maximum temperatures for vegetative growth are 21°C–27°C with sufficient moisture. During flowering, daily maximum temperatures of 27°C–32°C with sufficient moisture are optimal. Each boll requires 415–610 DD15C heat units to mature from a white bloom into an open boll. High temperatures above 32°C may decrease boll size and increase the amount of time for bolls to reach maximum weight (El-Zik, 1982; Oosterhuis and Jernstedt, 1999). Too much water from rain or irrigation early in the plant’s growth will cause the plant to set its first reproductive branch too high on the main stem as a result of excessive internode elongation. On the other hand, early water stress or drought will cause the setting of reproductive branches too low on the stem because internode length is reduced. Rain, cloudy weather and excessively high temperatures can cause an increase in square and boll shedding (Reddy et al., 1998; Guinn, 1998; Eaton et al., 1954; Pettigrew, 1994). Rain or irrigation on open flowers during the pollination process can rupture the pollen, resulting in poorly pollinated flowers and, subsequently, square shed (Burke, 2003; Pennington and Pringle, 1987). Even without rain, cloudy weather decreases photosynthesis and may result in square and small boll shed. High temperatures prior to anthesis can prevent the production of viable pollen (Meyer, 1969) and cause the stigma to extend; this prevents fertilization, resulting in young square abortion. When the temperature rises above 35°C, more of the anthers produced are sterile and therefore flower survival and fruit production are poor during that time.

As this shows, there are a number of abiotic stress factors, particularly moisture surpluses and deficits, high and low temperatures, and low light, that impose limitations on the growth and development and therefore the yield of a cotton crop. Monitoring these factors is a requirement that allows growers to understand why yields may be reduced due to certain environmental effects. Climate and environmental monitoring should be done at the local level. The normal climate of a location remains more consistent over time and therefore needs to be considered prior to the season. The normal weather patterns during the production season have to be identified and then taken advantage of in order to maximize production and profitability. Knowledge of the location’s climate, both atmospheric and edaphic, verifies the location’s suitability for sustaining crop production. Soil moisture and temperature need to be monitored prior to planting to promote quick and healthy germination and establishment of a healthy, uniform plant stand. Soil moisture during the entire season is critical in order to maximize yields and either extreme, of too much or too little, stresses the plant and potentially limits the plant’s yield. Air temperatures are important throughout the growing season, but are most critical at planting time.

10.1.6 **Agrometeorological services available for cotton production**

Cotton that is grown commercially has to produce yields that are at or above a point at which a sustainable economic profit is attained. The economics of a particular region will ultimately determine what yield is acceptable. In order for growers to be able to monitor in-season environmental conditions, utilize historical climatic information and attempt to take advantage of or divert ill effects of weather, pertinent weather and crop information needs to be made available to them. Research on the interactions between existing and new cultivars and environmental conditions needs to be completed and released to growers in a timely and continuous manner. Agrometeorological information and products are vital tools for growers to have available for management and economical decision-making. Governments, agencies, universities and organizations are ideally positioned to make these data and products available to individual growers. Many countries or areas have groups such as these providing these services to growers, and some countries are developing the relevant programs. These agrometeorological services need to be developed and maintained in all cropping areas worldwide.

Local weather information can be obtained from the Internet, national or regional weather services, and local meteorological professionals. Data may be collected near population centers and thus may not represent local agricultural interests or needs. Several areas have established agricultural weather station networks, however, and their data are available through the supporting group or agency. In the United States, agricultural weather networks are supported by individuals, cooperatives, corporations, agencies, universities and organizations. The data are usually
accessibility via the Internet and agrometeorological products are made available to their users. Users may monitor current or historical weather data, depending on the network’s capabilities, for decision-making in cotton production on matters ranging from planting, utilizing soil temperatures and harvesting, to monitoring heat units after a cracked boll for defoliation applications. Producers may also utilize the data in-season for monitoring square and boll shed or crop protection applications.

One example of a product provided to cotton producers by a university is a cotton-planting recommendation map that graphically depicts over the entire state when the next five-day forecast temperatures are suitable for cotton planting (MSU-DREC, 2006). Another example of a researched agrometeorological tool is monitoring maturity of the cotton plant utilizing the node above white flower (NAWF) mapping technique (Bourland et al., 2001). NAWF can be utilized effectively to plan and schedule sequential events, such as termination of crop-enhancing and protection applications, defoliation and harvest by monitoring both the physiological stage of the cotton plant and heat unit accumulation (Harris et al., 1997; Tugwell et al., 1998; Siebert et al., 2006). On a global scale, global weather and crop information is being compiled and distributed by the World Agricultural Outlook Board (WAOB) of the United States Department of Agriculture (USDA) in its publications, which are available through the mail or on the Internet at http://www.usda.gov/ocew/weather/pubs/index.htm.

10.2 AGROMETEOROLOGY AND GROUNDNUT PRODUCTION

10.2.1 Importance of groundnut in various climates

10.2.1.1 General

Groundnut (Arachis hypogaea L.) is an annual legume that is also known as peanut, earthnut, monkeynut and goobers. It is the thirteenth most important food crop and fourth most important oilseed crop in the world. Groundnut seeds (kernels) contain 40–50 per cent fat, 20–50 per cent protein and 10–20 per cent carbohydrate. Groundnut seeds are a nutritional source of vitamin E, niacin, folic acid, calcium, phosphorus, magnesium, zinc, iron, riboflavin, thiamine and potassium. Groundnut is consumed directly as raw, roasted or boiled kernels, or in the form of oil extracted from the kernel and used for cooking. It is also used as animal feed (oil pressings, seeds, green material and straw) and as industrial raw material (oil cakes and fertilizer).

These multiple uses of the groundnut plant make it an excellent cash crop for domestic markets as well as for foreign trade in a number of developing and developed countries.

Cultivated groundnut originates from South America (Weiss, 2000). It is one of the world’s most popular crops, and it is under cultivation in more than 100 countries on six continents (Nwokolo, 1996). It is grown on 25.2 million hectares with a total production of 35.9 million tonnes (FAO, 2006). The major groundnut-growing countries are India (accounting for 26 per cent of the total area devoted to groundnut cultivation), China (19 per cent) and Nigeria (11 per cent). Its cultivation is mostly confined to the tropical countries ranging from 40°N to 40°S. Major groundnut-producing countries are: China (with 40.1 per cent of total production), India (16.4 per cent), Nigeria (8.2 per cent), United States (5.9 per cent) and Indonesia (4.1 per cent).

10.2.1.2 Production environments in major producing countries

10.2.1.2.1 China

Groundnut has a long history of cultivation in China and historical accounts record its cultivation as early as the late thirteenth century (Shuren, 1995). Groundnut is now one of the main cash and oil crops in China. Area under groundnut in China accounts for about 25 per cent of the total area devoted to oilseed crops. In high-income provinces, groundnut is grown for oil production and export. In other provinces it is grown primarily for food, especially as a snack (Yao, 2004). Groundnut is becoming more attractive to farmers due to its higher net profit per unit area compared with other crops in several parts of China.

The main groundnut-producing areas in China are Shandong, Henan, Guangdong, Hebei and Guangxi, which account for more than 60 per cent of the cultivated area and total production. Shandong is the leading province (Shuren, 1995). It accounts for 23 per cent of the area and 33 per cent of total production in the country (Shufen et al., 1998). Groundnut is grown in rotation with various crops in diverse cropping systems in different regions. In Shandong province, groundnut is grown in summer following winter wheat. It is also rotated with sweet potato, corn, tobacco and vegetables in other regions.

As for production constraints, about 70 per cent of the total groundnut cultivation areas are hilly-mountainous, infertile, dryland low-lying areas that have a low capacity to withstand drought or waterlogging.
Poor farming practices such as the lack of quality seeds and continuous monocropping are considered constraints for groundnut production in China.

10.2.1.2.2 India

Among oilseeds crops in India, groundnut accounts for about 50 per cent of planted area and 45 per cent of oil production. In India, about 75 per cent of the groundnut area lies in a low to moderate rainfall zone (parts of the peninsular region and western and central regions) with a short period of distribution (90–120 days). Based on rainfall patterns, soil factors, diseases and pest situations, the groundnut-growing area in India has been divided into five zones. In India, most of the groundnut production is concentrated in five states – Gujarat, Andhra Pradesh, Tamil Nadu, Karnataka and Maharashtra. These five states account for about 86 per cent of the total area under peanut cultivation. The remaining peanut-producing area is scattered among the states of Madhya Pradesh, Uttar Pradesh, Rajasthan, Punjab and Orissa. Although the crop can be grown in all seasons, it is grown mainly in the rainy season (kharif), running from June to September. The kharif season accounts for about 80 per cent of the total groundnut production. In the southern and southeastern regions, groundnut is grown in rice fallows during the post-rainy season (rabi), from October to March. If irrigation facilities are available, groundnut can be grown from January to May as a spring or summer crop. Monsoon variations cause major fluctuations in groundnut production in India. Groundnut is grown under different cropping systems, including sequential cropping, multiple cropping and intercropping (Basu and Ghosh, 1995).

As for production constraints, because groundnut is grown mainly as a rained crop, there is a high level of fluctuation in production depending on the rainfall. Productivity is curtailed by drought stress, the use of low levels of inputs by smallholders and marginal farmers in dryland areas, a high incidence of foliar fungal diseases and attack by insect pests.

10.2.1.2.3 United States of America

Most of the groundnut produced around the world is consumed as food domestically. Although the United States produces about 10 per cent of the world’s groundnut harvest, however, it is a leading exporter and accounts for about 25 per cent of the world’s groundnut trade (Smith, 2002). Groundnut is grown in three regions of the United States: the South-East (including Georgia, Alabama and Florida), the South-West (Texas, Oklahoma and New Mexico) and the Virginia Carolinas region (Virginia, North Carolina and South Carolina). Most of the groundnut-producing areas are in the humid zone (the South-East), although some of them (mostly in the South-West) have semi-arid conditions (Hammons, 1982; Isleib and Wyne, 1991).

As for production constraints, temperature is the major limiting factor for peanut yield in northern states, since a minimum of 3 000 growing degree-days (with a base of 50°F) is required for proper growth and development (Robinson, 1984). A peanut crop will not reach optimum maturity for a marketable yield to justify commercial production in areas with fewer heat units during the growing season.

10.2.1.2.4 Nigeria

Groundnut is one of the most popular commercial crops in Nigeria north of latitude 10° N. Groundnut kernels, cake and oil account for as much as 20 per cent of the total export earnings of this West African country, while satisfying the local requirements for edible nuts. The husk (shell) is used as fuel, roughage, litter for livestock, mulch, manure and soil conditioner. The key areas of production have changed over the years.

Major groundnut-producing areas are located in the Sudan and Northern Guinea ecological zones, where the soil and agroclimatological conditions are favourable (Misari et al., 1980). Temperatures are moderately warm and relatively stable during the growing season at 20°C–25°C. The savanna zone in Sudan receives adequate rainfall for the production of groundnut. The crop is grown usually as a component of a variety of crop mixtures including sorghum, millet, cowpea and maize (Misari et al., 1988). There are two main varieties grown in Nigeria: long-season varieties maturing in 130 to 145 days and short-season varieties maturing in 90 to 100 days.

As for production constraints, groundnut production in Nigeria faces problems that are numerous and complex. Drought, coupled with the groundnut rosette epidemic in 1975, resulted in a decline in groundnut production. This has led to a southward shift of the suitable climatic zone for groundnut production. Heavier soils in the south compared with the sandy soils of the Sudan savanna make harvesting difficult, however. Diseases such as the rosette, early leaf spot, late leaf spot and rust have been on the increase. Leaf spot attack severely reduces yield.

10.2.1.2.5 Indonesia

Groundnut is the second most important food legume crop after soybean in Indonesia (Machmud and Rais, 1994). Groundnut is grown mostly at low Elevations (up to 500 m) in nine provinces: West
Java, Central Java, Yogyakarta, East Java, South Kalimantan, Lampung, Bali, West Nusa Tenggara and South Sulawesi. The total annual rainfall figures in the leading production areas range from 2,080 to 3,442 mm. Most of the groundnut (66 per cent) is produced under rainfed conditions (Saleh and Adisarwanto, 1995). In drier areas, groundnut is generally grown in mixed cropping with maize or cassava, whereas in wetter areas, it is generally grown during the dry season as a single crop. Farmers grow mostly small-seeded and early-maturing varieties (85 to 90 days).

As for production constraints, major climatic and biotic constraints identified for low production are: drought during the reproductive stage; diseases such as leaf spot and rust; and insects such as aphids, jassids and thrips. The major insect pest is Aproaerema modicella, and the most important diseases are bacterial wilt (Pseudomonas solanacearum), leaf spot (Cercospora sp.), rust (Puccinia arachidis) and groundnut mottle virus.

10.2.2 Agroclimatology of groundnut

Groundnut is essentially a tropical plant and requires a long and warm growing season. The favourable climate for groundnut is well-distributed rainfall of at least 500 mm during the crop-growing season, accompanied by an abundance of sunshine and relatively warm temperature. Temperature in the range of 25°C to 30°C is optimum for plant development (Weiss, 2000).

Once established, groundnut is drought-tolerant, and to some extent it also tolerates flooding. Rainfall of 500 to 1,000 mm will allow commercial production, although crop can be produced on as little as 300 to 400 mm of rainfall. Groundnut thrives best in well-drained sandy loam soils, as light soil helps in easy penetration of pegs and their development and their harvesting. The productivity of groundnut is higher in soils with pH between 6.0 and 6.5.

10.2.2.1 Rainfall or soil moisture

Rainfall is the most significant climatic factor affecting groundnut production, as 70 per cent of the crop area is found in semi-arid tropical regions characterized by low and erratic rainfall. Low rainfall and prolonged dry spells during the crop growth period were reported to be main reasons for low average yields in most of the regions of Asia and Africa, including India (Reddy et al., 2003), China (Zeyong, 1992) and several parts of Africa (Camberlin and Diop, 1999). Zeyong (1992) reported that drought is the most important constraint on groundnut production in China, especially in parts of northern China where rainfall is less than 500 mm yr⁻¹. Naing (1980) reported that rainfall was the main factor determining yield in Myanmar. Camberlin and Diop (1999) reported that after removing decadal trends, almost half of the variance in groundnut production in Senegal can be explained by rainfall variability, especially during the early part of the rainy season (July–August). Persistent droughts and insufficient rainfall represent one of the greatest constraints on groundnut crop in Senegal. Groundnut requiring average rainfall of 600–1,200 mm per year under Senegal’s climatic conditions is receiving 500–700 mm of rainfall per year (Badiane, 2001). Duivenbooden et al. (2002) reported that groundnut production in Niger is significantly determined by rainfall from July to September.

In India groundnut yields were reported to be vulnerable from year to year because of large interannual variation in rainfall (Sindagi and Reddy, 1972). Bhargava et al. (1974) reported that 89 per cent of yield variation over four regions of India could be attributed to rainfall variability in the August to December growing period. Challinor et al. (2003), analysing 25 years of historical groundnut yields in India in relation to seasonal rainfall, concluded that rainfall accounts for over 50 per cent of variance in yield. Gadgil (2000) observed that the variation in groundnut yield in the Anantapur district arises to a large extent from the variation in the total rainfall during the growing season. It was observed that seasonal rainfall up to 50 cm is required to sustain a successful groundnut crop in this region.

Yield in this region can be indirectly related to El Niño events: in 87 per cent of El Niño years the Anantapur region received less than 50 cm of rainfall, which in turn affected the groundnut yield. In Anantapur, the pod yield of groundnut showed a highly significant curvilinear relationship with the use of moisture, namely, adding rainfall and soil moisture (AICRPAM, 2003). A total moisture use of 350–380 mm was found to be optimum for obtaining a maximum yield; a moisture use of either less than this amount or more reduced pod yield. Nonetheless, Popov (1984) and Ong (1986) showed a poor relationship between groundnut yield and seasonal rainfall, thus highlighting that rainfall distribution is more important to groundnut yield than the amount of rainfall.

The importance of rainfall distribution to groundnut yield is well appreciated, but experimental evidence is poorly documented (Ong, 1986). Work in a controlled environment at Nottingham University, United Kingdom, showed a crop yield to be four times greater than the yield of a crop...
that used the same amount of water, but was irrigated during the vegetative phase only (ODA, 1984). Results from a series of experiments at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, 1984) showed that early stress or lack of rainfall/soil moisture between 29 and 57 days after sowing did not influence pod yield significantly, whereas pod yields increased by 150 kg/ha/cm of water applied during the seed-filling stage (93–113 days after sowing). The pod yield of groundnut and rainfall received between pod formation and maturity were positively correlated in a rainfed crop grown in the semi-arid region of Andhra Pradesh in India (Subbaiah et al., 1974).

In the subtropical environment of south-east Queensland, Australia, soil water deficits occurring during flowering and up to the start of the pod growth phase significantly reduced pod yields (in a range of 17–25 per cent) relative to the well-watered control plots for two Spanish and two Virginia cultivars (Wright et al., 1999). The reduction in yield was greatest when severe stress occurred during the pod-filling phase. Several other reports also observed the pod development stage to be most sensitive to moisture deficit (Rao et al., 1985; Stirling et al., 1989; Patel and Gangavani 1990; Meisner 1991; Ramachandrappa et al., 1992). Analysis of the relationship between simulated groundnut yield and climate in Ghana showed that yield was predominantly influenced by rainfall from flowering to maturity (Christensen et al., 2004). Naveen et al. (1992) found that water stress imposed during the flowering and pegging stages of JL-24 produced the greatest reductions in pod yield, followed by water stress at early and late pod stages.

Prabawo et al. (1990) reported that irrigation applied before and/or after early pod-filling stages increased pod yields of Spanish-type groundnuts (100 day) to 2.4 t ha⁻¹ compared with 0.53 t ha⁻¹ in a dryland groundnut crop. Nageswara Rao et al. (1985) confirmed that irrigations could be withheld during much of the vegetative period without any apparent effect on pod yield, implying that water stress during the vegetative stage has no effect on yield. Nautiyal et al. (1999) proved that soil moisture deficit for 25 days during the vegetative phase was beneficial for growth and pod yield of groundnut, while Stirling et al. (1989) observed the insensitivity of pod yield to early moisture deficit. Sivakumar and Sharma (1986) imposed drought stress or a soil moisture deficit at all the growth phases of groundnut during three growing seasons and observed that stress from emergence to pegging gave increased yields relative to the control group in the three years of the study, while stress at other stages decreased the yield.

Not just yields, but other yield attributes, growth and development are affected by soil moisture deficit or water stress. The start of flowering and pod elongation are delayed by drought stress (Boote and Ketting, 1990). The rate of flower production is reduced by drought stress during flowering but the total number of flowers per plant is not affected due to an increase in the duration of flowering (Gowda and Hegde, 1986; Meisner and Karnok, 1992). Boote and Hammond (1981) reported a delay of 11 days in flowering when drought was imposed between 40 and 80 days after sowing. Stansell and Pallas (1979) found that the percentage of mature kernels was reduced to 34 per cent of the control when drought was imposed 36–105 days after sowing.

Moisture stress also affects physiological characteristics such as photosynthesis, stomatal conductance, leaf water potential, radiation- and water-use efficiencies, and partitioning of dry matter (Williams and Boote, 1995). Bhagisari et al. (1976) observed large reductions in photosynthesis and stomatal conductance as the relative water content of groundnut leaves decreased from 80 to 75 per cent (due to moisture stress). Subramanian and Maheswari (1990) reported that leaf water potential, transpiration rate and photosynthesis rate decreased progressively with increasing duration of water stress. Black et al. (1985) recorded lower water potential and stomatal conductance when moisture stress was imposed. Clavel et al. (2004) reported that water deficit decreased leaf area index, relative water content and transpiration about three weeks after the occurrence of water deficit at the soil level.

Collino et al. (2001) observed that the fraction of photosynthetically active radiation intercepted and the harvest index were reduced under water stress. In Argentina, under water stress conditions, groundnut varieties (Florman INTA and Manfredi 393 INTA) produced significantly reduced water use efficiency compared with the irrigated regime (Collino et al., 2000). Vorasoot et al. (2003) observed a drastic reduction in yield and also in yield-attributing characteristics such as total dry weight and shelling percentage when plants were grown at 25 per cent of the field capacity of the soil.

10.2.2.2 Growth stages and water use

The growth stages of groundnut were described and defined by Boote (1982). This widely adopted system describes a series of vegetative (V) and reproductive (R) stages. The total water use by a groundnut crop is controlled by climatic conditions, in addition to
agronomic and varietal factors. A summary of the reported water use of groundnut (reproduced from Sivakumar and Sharma, 1986) in Table 10.2.1 shows that water use varies from 250 mm in the rainfed conditions to 830 mm under irrigated conditions (with irrigation at weekly intervals). Naveen et al. (1992) reported that spraying of 3 per cent kaolinite during dry periods at 35 and 55 days after sowing showed significant yield increases over control.

From the lysimetric studies in groundnut (ICGS-76) at Rakh Dhiansar, in the Jammu region of India, water requirements for the crop were estimated at 494 mm and 500 mm in two individual years and water use for the crop was observed to be at its highest (crop coefficient 1.9) during the pod formation stage (AICRPAM, 1997, 1998). In FAO Irrigation and Drainage Paper No. 33 (FAO, 1979), Doorenbos and Kassam worked out water requirements for each growing stage, as well as the total water requirement for the crop. The water requirement of the crop ranged from 500 to 700 mm for the total growing period. The growing period of the crop is divided into five stages.

Table 10.2.1 Summary of reported values of total water use (mm) for groundnut (Sivakumar and Sharma, 1986)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Total water use (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ali et al. (1974)</td>
<td>530</td>
<td>Irrigated at 60% water depletion</td>
</tr>
<tr>
<td>Angus et al. (1983)</td>
<td>250</td>
<td>Rainfed</td>
</tr>
<tr>
<td>Charoy et al. (1974)</td>
<td>510</td>
<td>Rainfed</td>
</tr>
<tr>
<td>Cheema et al. (1974)</td>
<td>337</td>
<td>Rainfed</td>
</tr>
<tr>
<td></td>
<td>597</td>
<td>Irrigated at 40% water depletion</td>
</tr>
<tr>
<td>Kadam et al. (1978)</td>
<td>342</td>
<td>Rainfed</td>
</tr>
<tr>
<td>Kassam et al. (1975)</td>
<td>438</td>
<td>Rainfed</td>
</tr>
<tr>
<td>Reddy et al. (1980)</td>
<td>560</td>
<td>Irrigated, winter months</td>
</tr>
<tr>
<td>Reddy et al. (1978)</td>
<td>417</td>
<td>Rainfed</td>
</tr>
<tr>
<td>Reddy and Reddy (1977)</td>
<td>505</td>
<td>Irrigated at 25% water depletion</td>
</tr>
<tr>
<td>Panabokke (1959)</td>
<td>404</td>
<td>October to January</td>
</tr>
<tr>
<td>Keese et al. (1975)</td>
<td>500–700</td>
<td>Irrigated at 50% water depletion</td>
</tr>
<tr>
<td>Samples (1981)</td>
<td>450–600</td>
<td>Irrigated at 50% water depletion</td>
</tr>
<tr>
<td>Nageswara Rao et al. (1985)</td>
<td>807–831</td>
<td>Irrigated at 7–10 day interval during winter months</td>
</tr>
</tbody>
</table>

The stages, their duration and crop coefficients for individual stages are presented in Table 10.2.2. Data in this table show that the midseason stage (pod formation and filling) requires higher water quantities, as indicated by the high crop coefficient value. In a field experiment conducted during two summer seasons in eastern India with JL-24, a bunch variety, water use recorded for three treatments with applied irrigation of 0.9, 0.7 and 0.5 of cumulative pan evaporation was equal to 434, 391 and 356 mm, respectively (Bandopadhyay et al., 2005). A maximum average crop coefficient ($K_c$) value of 1.19 occurred around nine weeks after sowing in the same experiment.

10.2.2.3 Temperature

Temperature has been identified as a dominant factor for controlling the rate of development of groundnut (Cox, 1979). Every crop has its cardinal temperatures, which are the base ($T_b$), optimum ($T_o$) and maximum temperatures ($T_m$). These are defined respectively as: temperatures above which growth and development begin, temperatures at which growth and development are maximum, and temperatures above which growth

### Table 10.2.1 Summary of reported values of total water use (mm) for groundnut (Sivakumar and Sharma, 1986)

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<tr>
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<td>337</td>
<td>Rainfed</td>
</tr>
<tr>
<td></td>
<td>597</td>
<td>Irrigated at 40% water depletion</td>
</tr>
<tr>
<td>Kadam et al. (1978)</td>
<td>342</td>
<td>Rainfed</td>
</tr>
<tr>
<td>Kassam et al. (1975)</td>
<td>438</td>
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</tr>
<tr>
<td>Reddy et al. (1980)</td>
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</tr>
</tbody>
</table>
and development cease. Mohamed (1984) reported cardinal temperatures for seed germination in 14 contrasting genotypes of groundnut, which are shown in Table 10.2.3. These values indicate that \( T_b \) does not vary much across genotypes (ranging from 8°C to 11.5°C), whereas optimum temperatures (29°C–36.5°C) and maximum temperatures (41°C–47°C) vary much more. Base temperature was reported to be higher during the reproductive phase (3°C–10°C higher) than during the vegetative phase (Angus et al., 1981). In contrast, Leong and Ong (1983) showed \( T_b \) to be conservative for many processes and phases of groundnut cv Robut 33–1. Optimum temperatures for different growth and developmental processes of the crop are presented in Table 10.2.4. Optimum temperatures for different processes range between 23°C and 30°C. Optimum temperature for germination and leaf appearance was observed to be higher than for other processes. Williams et al. (1975) reported that the optimum temperature for vegetative growth of groundnut plants was in the range of 25°C–30°C, while that for reproductive growth was lower (20°C–25°C).

### Table 10.2.2. Crop coefficients \((K_c)\) per crop stage for groundnut

<table>
<thead>
<tr>
<th>Crop Stage</th>
<th>Duration (days)</th>
<th>Crop coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial stage</td>
<td>15–35</td>
<td>0.4–0.5</td>
</tr>
<tr>
<td>Development stage</td>
<td>30–45</td>
<td>0.7–0.8</td>
</tr>
<tr>
<td>Midseason stage</td>
<td>30–50</td>
<td>0.95–1.1</td>
</tr>
<tr>
<td>Late-season stage</td>
<td>20–30</td>
<td>0.7–0.8</td>
</tr>
<tr>
<td>Harvest stage</td>
<td></td>
<td>0.55–0.6</td>
</tr>
</tbody>
</table>

### Table 10.2.3. Base \((T_b)\), optimum \((T_o)\) and maximum \((T_m)\) temperatures of 14 groundnut cultivars for seed germination (Mohamed, 1984)

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>( T_b )</th>
<th>( T_o )</th>
<th>( T_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valencia R2</td>
<td>8</td>
<td>35</td>
<td>43</td>
</tr>
<tr>
<td>Flammings</td>
<td>8</td>
<td>34.5</td>
<td>42</td>
</tr>
<tr>
<td>Makulu Red</td>
<td>8.5</td>
<td>29</td>
<td>42</td>
</tr>
<tr>
<td>ICG 30</td>
<td>8</td>
<td>36</td>
<td>44</td>
</tr>
<tr>
<td>EGRET</td>
<td>9</td>
<td>29</td>
<td>43</td>
</tr>
<tr>
<td>ICG 47</td>
<td>9</td>
<td>36.5</td>
<td>47</td>
</tr>
<tr>
<td>Robut 33–1</td>
<td>10</td>
<td>36.5</td>
<td>46</td>
</tr>
<tr>
<td>TMV 2</td>
<td>10</td>
<td>36</td>
<td>42</td>
</tr>
<tr>
<td>MK 374</td>
<td>10</td>
<td>36</td>
<td>44</td>
</tr>
<tr>
<td>Plover</td>
<td>10.5</td>
<td>34</td>
<td>42</td>
</tr>
<tr>
<td>ICG 21</td>
<td>11</td>
<td>35.5</td>
<td>45</td>
</tr>
<tr>
<td>M 13</td>
<td>11</td>
<td>34</td>
<td>45</td>
</tr>
<tr>
<td>Swallow</td>
<td>11</td>
<td>29</td>
<td>42</td>
</tr>
<tr>
<td>N. Common</td>
<td>11.5</td>
<td>29</td>
<td>41</td>
</tr>
<tr>
<td>Ranges</td>
<td>8–11.5</td>
<td>29–36.5</td>
<td>41–47</td>
</tr>
</tbody>
</table>

### Table 10.2.4. Optimum temperature for vegetative and reproductive growth and development of groundnut

<table>
<thead>
<tr>
<th>Trait</th>
<th>Optimum ( t ) (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed germination</td>
<td>28–30</td>
<td>Mohamed et al., 1988</td>
</tr>
<tr>
<td>Seedling growth</td>
<td>28</td>
<td>Leong and Ong, 1983</td>
</tr>
<tr>
<td>Leaf appearance and leaf area growth</td>
<td>28–30</td>
<td>Fortainer, 1957; Cox, 1979</td>
</tr>
<tr>
<td>Branching and stem growth</td>
<td>28</td>
<td>Leong and Ong, 1983; Ketring, 1984;</td>
</tr>
<tr>
<td>Flower production</td>
<td>25–28</td>
<td>Fortainer, 1957; Wood, 1968; Cox, 1979</td>
</tr>
<tr>
<td>Pollen production</td>
<td>23</td>
<td>Prasad et al., 1999</td>
</tr>
<tr>
<td>Pollen viability</td>
<td>23</td>
<td>Prasad et al., 1999, 2000; Kakani et al., 2002</td>
</tr>
<tr>
<td>Peg formation</td>
<td>23</td>
<td>Prasad et al., 1999</td>
</tr>
<tr>
<td>Pod formation, pod growth and seed yield</td>
<td>23–26</td>
<td>Williams et al., 1975; Cox, 1979; Dreyer et al., 1981</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prasad et al., 1999, 2003</td>
</tr>
<tr>
<td>Root growth</td>
<td>23–25</td>
<td>Ahring et al., 1987; Prasad et al., 2000</td>
</tr>
<tr>
<td>Harvest index</td>
<td>23–27</td>
<td>Prasad et al., 1999; Craufurd et al., 2002</td>
</tr>
<tr>
<td>Nitrogen fixation</td>
<td>25</td>
<td>Nambiar and Dart, 1983</td>
</tr>
</tbody>
</table>
The duration of the crop is very much influenced by temperature. Bell et al. (1992) reported an early bunch variety that matures in 120–130 days after sowing at a mean temperature of 23°C, while the same variety matures in 105 days after sowing when grown in a coastal environment with slightly higher mean temperatures (25°C). Other authors have also reported such strong effects of temperature on groundnut phenology (Leong and Ong, 1983; Bagnall and King, 1991). Crop duration was shortest in humid tropical and subtropical environments, with crop maturity apparently affected by both high and low temperatures (Bell and Wright, 1998). Williams et al. (1975) reported that the total growing period of the crop was shortened from 176 days at a temperature of 18°C to 151 days at 23°C. The duration of groundnut cv Robut 33-1 from sowing to the end of seed filling increased from 95 days at 31°C to 222 days at 19°C. Not only was the duration of the crop influenced by temperature, but also the growth and yield traits. Craufurd et al. (2000) exposed eight genotypes to either high (day/night temperature of 40°C/28°C) or optimum (30°C/24°C) temperature from 32 days after sowing to maturity and reported that rates of appearance of leaves and flowers were faster at 40°C/28°C when compared with 30°C/24°C. As groundnut pods are developed under the soil, it is important to understand the influence of soil temperature. Prasad et al. (2000) reported that exposure to high air and/or high soil temperature (38°C/22°C) significantly reduced total dry matter production, partitioning of dry matter to pods, and pod yields in two cultivars. High air temperature had no significant effect on total flower production but significantly reduced the proportion of flowers setting pegs (fruit set), while in contrast, high soil temperature significantly reduced flower production, production of pegs forming pods, and 100-seed weight. Furthermore, the effects of high air and soil temperatures were mostly additive. Higher temperature promoted greater vegetative growth and higher photosynthesis in three genotypes of groundnut, but the reproductive growth was decreased due to greater flower abortion and smaller seed size (Talwar et al., 1999; Prasad et al., 2003).

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A modified bilinear model most accurately described the response of percentage pollen germination and maximum pollen tube length to temperature. Based on temperature response, genotypes 55–43, ICG 1236, TMV-2 and ICGS 11 were grouped as tolerant to high temperature and genotypes Kadiri-3, ICGV 92116 and ICGV 92118 were grouped as susceptible genotypes. Ntare et al. (2001) observed that the pod yield of most of the 16 genotypes of groundnut tested under actual field conditions of the Sahelian region of Africa declined by more than 50 per cent when maximum temperatures averaged around 40°C and occurred during flowering and pod formation. Craufurd et al. (2002) observed that high temperature (38°C/22°C) from 21 to 90 days after planting reduced total dry weight by 20 to 35 per cent, seed harvest index by 0 to 65 per cent and seed dry weight by 23 to 78 per cent. Genotypic differences in response to temperature were noticed and reductions in total dry matter, pod and seed dry weight and harvest index at high temperatures were noticed only in susceptible genotypes.

The interactive effects of temperature and other environmental factors are less understood and need further attention. Prasad et al. (2003) studied the effects of temperature in combination with elevated CO₂ on various physiological and yield processes of groundnut. At ambient CO₂ (350 ppm CO₂), seed yield decreased progressively by 14 per cent, 59 per cent and 90 per cent as temperature increased from 32°C/22°C (daytime maximum/night-time minimum) to 36°C/26°C, 40°C/30°C and 44°C/34°C, respectively. A similar percentage decrease in seed yield occurred at temperatures above 32°C/22°C at elevated CO₂, despite greater photosynthesis and vegetative growth at elevated CO₂. The seed harvest index decreased from 0.41 to 0.05 as temperature...
increased from 32°C/22°C to 44°C/34°C under both ambient and elevated CO₂. A 30 per cent decrease in pod yield was observed due to lower thermal and photoperiodic conditions during the reproductive phase of groundnut (AICRPAM, 1998).

Similarly, temperature (expressed as degree-day) and rainfall during the reproductive period positively influenced the pod yield and together they explained 86 per cent of yield variation (AICRPAM, 1997). Temperature and light intensity affected flower numbers of groundnut varieties and these changes were also well correlated with growth-related changes in leaf number and pod dry weight (Bagnall and King, 1991). In crop models, the optimum temperature for canopy photosynthesis was between 24°C and 34°C (daytime mean temperature), with linear reductions below 24°C down to 5°C and with linear reductions above 34°C up to 45°C (Boote et al., 1986). Vijaya Kumar et al. (1997), while analysing the variability of groundnut yield at three locations across varied soil and climatic conditions in relation to temperature and rainfall, observed that the Bangalore region, despite experiencing higher rainfall than the Anantapur and Anand regions, had a lower average pod yield owing to mean temperatures that were lower than optimum.

### 10.2.2.4 Thermal time or accumulated heat unit requirements of groundnut

Phenological development of groundnut responds primarily to heat unit accumulation. Leong and Ong (1983) calculated heat unit requirements for different phenological stages (Table 10.2.5). Two papers reporting on heat units to flowering for groundnut have suggested a base temperature of 13°C–14°C, below which reproductive development stops (Emery et al., 1969; Mills, 1964). In 16 sowings ranging from the wet tropics in Indonesia to the elevated subtropics in Australia, the harvest date corresponded to the accumulation of about 1 800 (base temperature of 9°C) growing degree-days (GDD) after sowing (Bell and Wright 1998).

Thermal units required for groundnut cultivars to reach maturity were 2 247 GDD in Sudan (Ishaq, 2000). Ong (1986) reported a maturity index or thermal units of 2 000 GDD for the cultivars in warm regions of India – at a base temperature of 10°C. The varieties TMV-2 and Robut 33-1 grown in the semi-arid Anantapur region of India required 1 732 GDD and 1 839 GDD, respectively (AICRPAM, 1998). In the same year, Robut 33-1 grown in Bangalore, a semi-arid region of India, took 1 491 GDD. The thermal time requirement for maturity of the same variety seems to be different for different sowing dates and locations.

#### 10.2.2.5 Photoperiod or day length

Early studies in controlled environments showed that phenology of groundnut is not affected by day length (Fortainer, 1957). Later studies showed that pod yield is significantly influenced by day length, however (Ketring, 1979; Witzenberger et al., 1988). It is now well established that long days promote vegetative growth at the expense of reproductive growth and increased crop growth rate, decreased partitioning of photosynthesis to pods, and decreased duration of effective pod-filling phase (Ketring, 1979; Witzenberger et al., 1988; Nigam et al., 1994, 1998). Some contradictory results on the influence of day length on the duration of reproductive growth were reported. While Sengupta et al. (1977) found that a day length shorter or longer than 10 h delayed flowering, Ketring (1979) did not observe any effect of day length (8, 12 and 16 h) on flower initiation. The contrasting results might have been obtained due to differences among cultivars, which are known to vary in response to photoperiod.

In a study by Bagnall and King (1991), flower, peg and pod numbers were consistently enhanced by

<table>
<thead>
<tr>
<th>Developmental process</th>
<th>Thermal time (GDDs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf production</td>
<td>56 per leaf</td>
</tr>
<tr>
<td>Branching</td>
<td>103 per branch</td>
</tr>
<tr>
<td>Time to first flowering</td>
<td>538</td>
</tr>
<tr>
<td>Time to first pegging</td>
<td>670</td>
</tr>
<tr>
<td>Time to first podding</td>
<td>720</td>
</tr>
</tbody>
</table>
short-day treatments for a range of groundnut varieties. Flower and peg numbers at 60–70 days from emergence were approximately doubled after 12 h day exposures compared to plants with 16 h days. The pod number, and therefore the yield, was more influenced by photoperiod than was flower or peg formation. Bell et al. (1991), while studying the effects of photoperiod on reproductive development of groundnut in a cool subtropical environment, observed that the numbers of pegs and pods and total pod weight per plant were reduced in long (16 or 17 h) photoperiods, but no effect of photoperiod was evident on time to first flower. It was further observed that the photoperiod responses were more significant in the environments where daily accumulations greater than 34°C–35°C were observed. Nigam et al. (1994) studied the effect of temperature and photoperiod and their interaction on plant growth, as well as partitioning of dry matter to pods, in three selected groundnut genotypes grown in growth chambers. It was observed that photoperiod did not significantly affect partitioning of dry matter to pods under a low temperature regime (18°C–22°C), but at higher temperatures (26°C–30°C) partitioning to pods was significantly greater under short days (9 h). This study provided evidence of genotypic variability for photoperiod–temperature interactions. In a field study on the effect of photoperiod on seed quality (Dwivedi et al., 2000), shelling percentage and palmitic acid increased under short-day (8 h) treatment compared with normal-day (12 h) treatment, while oil content, oleic and linolenic fatty acids and their ratio were unaffected.

10.2.2.6 Saturation deficit

Saturation deficit (SD) is an important agroclimatic factor for any crop, including groundnut, because it is a major determinant of potential evapotranspiration. Stomatal response to SD was found to limit the actual rate of transpiration (Black and Squire, 1979). Large SD accelerated the depletion of soil moisture reserves in the non-irrigated stands and greatly reduced leaf area index of groundnut, particularly in the driest treatment (Ong et al., 1985). Leaf number per plant and leaf size both decreased as SD increased, but SD had a greater impact on leaf size than on number. Turgor potential and leaf extension rate were also reduced at high SD. In another study on responses to SD conducted in glasshouses, developmental processes such as the timing of flowering, pegging and pod formation were found to be unaffected by SD, but the number of branches, flowers and pegs were reduced in the drier treatments (Ong et al., 1987). In the same study, in unirrigated stands, dry matter production in shoots was reduced by 40 per cent as the maximum SD increased from 1.0 to 3.0 kPa. Productivity per unit of water transpired decreased with increasing SD. Simmonds and Ong (1987) reported a strong dependence of transpiration on SD in groundnut and when SD exceeded 2 kPa, canopy expansion was restricted.

10.2.3 Further background information on groundnut

10.2.3.1 Relationship between diseases and weather

Several diseases and insect pests causing large losses in both yield and quality of seeds affect the groundnut crop. Weather indirectly influences the yield and quality through its effects on the occurrence and development of diseases and pests. Kolte (1985) reviewed diseases of groundnut in relation to weather conditions. The important plant diseases and meteorological conditions affecting them are described in this section.

10.2.3.1.1 Early and late leaf spots

Early and late leaf spots (Cercospora arachidicola and Puccinia personate) are considered the most important diseases of groundnut. They have been reported throughout the groundnut-growing areas of the world. Leaf spots cause huge yield loss in groundnut due to severe defoliation. Weather conditions conducive to the occurrence of early and late leaf spots as reported by different researchers are summarized in Table 10.2.6, which basically conveys that rainfall, leaf wetness and temperature are the most important factors for the occurrence and epidemiology of leaf spots.

10.2.3.1.2 Rust

Rust (Puccinia arachidis) has now become a disease of major economic importance in almost all the groundnut-growing areas of the world. It becomes devastating under conditions of high rainfall and humidity. In the postera planting season in Honduras and Nicaragua of Central America (Arneson, 1970) and in Venezuela, this disease becomes severe when the rainy season is almost over or when dew is abundant (Hammons, 1979). In India, a continuous dry period characterized by high temperature (>26°C) and low relative humidity (<70 per cent) is reported to delay rust occurrence and severity, whereas intermittent rain, high relative humidity and 20°C to 26°C temperature favour disease development (Siddaramaiah et al., 1980). In the Parbhani region of Maharashtra, India, Mayee (1987) observed that if average temperature of 20°C–22°C, relative
<table>
<thead>
<tr>
<th>Country</th>
<th>Disease</th>
<th>Weather conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>Early and late leaf spots</td>
<td>High relative humidity and dew</td>
<td>Wangikar and Shukla (1977)</td>
</tr>
<tr>
<td>United States</td>
<td>Early and late leaf spots</td>
<td>Rainfall and leaf wetness</td>
<td>Jensen and Boyle (1965)</td>
</tr>
<tr>
<td>Nigeria</td>
<td>Early leaf spots</td>
<td>Rainfall, relative humidity and low temperature</td>
<td>Garba et al. (2005)</td>
</tr>
<tr>
<td>India</td>
<td>Early and late leaf spots</td>
<td>Max. temp.: 31°C–35°C, Min. temp.: 18°C–23°C mean monthly rainfall of at least 60 mm</td>
<td>Venkataraman and Kazi (1979)</td>
</tr>
<tr>
<td>United States</td>
<td>Early and late leaf spots</td>
<td>Rainfall</td>
<td>Davis et al. (1993)</td>
</tr>
<tr>
<td>United States</td>
<td>Early and late leaf spots</td>
<td>Rainy days between June and September</td>
<td>Johnson et al. (1986)</td>
</tr>
<tr>
<td>United States</td>
<td>Early leaf spot</td>
<td>Shortly after the onset of rainfall</td>
<td>Smith and Crosby (1973)</td>
</tr>
<tr>
<td>India</td>
<td>Late leaf spot</td>
<td>Leaf wetness index of 2.3 or more</td>
<td>Butler et al. (1994)</td>
</tr>
<tr>
<td>India (Central)</td>
<td>Leaf spots</td>
<td>200–500 mm rainfall, 25°C–30°C temperature and 74% to 87% RH during crop season</td>
<td>Lokhande and Newaskar (2000); Mayee (1985)</td>
</tr>
<tr>
<td>United States</td>
<td>Leaf spots</td>
<td>No. of hours with RH ≥ 95% and minimum temperature</td>
<td>Jensen and Boyle (1966)</td>
</tr>
<tr>
<td>United States</td>
<td>Leaf spots</td>
<td>Temperature &gt;16°C and leaf wetness</td>
<td>Alderman and Beute (1986); Shew et al. (1988)</td>
</tr>
<tr>
<td>India</td>
<td>Leaf spots</td>
<td>Decrease in maximum temperature and increase in relative humidity</td>
<td>Adiver et al. (1998)</td>
</tr>
<tr>
<td>India</td>
<td>Late leaf spot</td>
<td>Temperature</td>
<td>Mayee (1989)</td>
</tr>
<tr>
<td>United States</td>
<td>Leaf spots</td>
<td>Rainfall, RH 80% and mean temp. of 23.2°C</td>
<td>Frag et al. (1992)</td>
</tr>
<tr>
<td>United States</td>
<td>Early leaf spots</td>
<td>Temperature and duration of wetness</td>
<td>Wu et al. (1999)</td>
</tr>
<tr>
<td>United States</td>
<td>Early leaf spots</td>
<td>Nearly 100% humidity and 16°C–25°C temperature</td>
<td>Alderman and Beute (1987)</td>
</tr>
<tr>
<td>India</td>
<td>Leaf spots</td>
<td>Max. temp. &lt;34°C, min. temp. &lt;22°C, morning RH &gt;82% and afternoon RH &gt;78%</td>
<td>Samui et al. (2005)</td>
</tr>
</tbody>
</table>
humidity above 85 per cent and three rainy days in a week prevail for two weeks, an outbreak of rust is likely. In the same region, on the basis of long-term observations of rust and weather conditions, key factors in the outbreak of rust were outlined (Sandhikar et al., 1989). If these conditions prevail for a week, an outbreak of rust is likely to occur within the next 15 days.

Mayee and Kokate (1987) observed that the incubation period of _Puccinia arachidis_ causing groundnut rust lengthened as the mean or maximum temperature rose, while it was negatively correlated with relative humidity. Multiple regression analysis of different combinations of environmental factors, including rainfall and evaporation rates, explained more than 96 per cent of the observed variation in incubation period. Mayee (1986) reported that the leaf rust epidemic commonly occurs during a prolonged dry spell after heavy showers. In their study of the influence of rainfall, temperature and relative humidity on groundnut leaf rust epidemiology, Lokhande et al. (1998) observed that rainfall of about 200 mm, temperature between 23.5°C and 29.4°C, and relative humidity in the range of 67 to 84 per cent are favourable weather conditions for initiation and development of this disease.

### 10.2.3.1.3 Sclerotinia blight

Sclerotinia blight (_Sclerotina minor_) occurs throughout groundnut-growing areas of the world in the tropics and in warmer parts of the temperate zone. Moisture, temperature and innoculum in the soil exert considerable influence on the disease (Onkarayya and Appa Rao, 1970). Moisture, soil temperature, vine growth and foliar canopy have been identified as factors that contribute to the onset and progress of this disease (Dow et al., 1988; Lee et al., 1990; Phipps, 1995a; Bailey and Brune, 1997). A study by Phipps (1995a) showed that rainfall usually preceded disease onset by 6 to 15 days in non-irrigated fields. Maximum and minimum air temperatures over the 15-day period prior to disease onset fluctuated between 32°C and 20°C, while maximum and minimum soil temperatures were between 30°C and 25°C, respectively. Optimum temperatures for sclerotial germination and infection of groundnut by _S. minor_ have been reported to be between 20°C and 25°C (Dow et al., 1988). In Texas, _S. minor_ was reported to be inactive in groundnut fields when soil temperature exceeded 28°C at the 5 cm depth (Lee et al., 1990). Although both moisture and temperature are commonly mentioned as significant factors affecting development of sclerotinia blight, evidence in the Virginia groundnut production area suggests that plant growth and rainfall are the primary forces at work in triggering outbreak of this disease (Phipps, 1995a).

#### 10.2.3.1.4 Collar rot

High soil and air temperatures predispose the groundnut plants to collar rot infection (_Aspergillus niger_) (Kolte, 1985). Development of different symptoms is dependent on temperature. Maximum seed rot occurs from 15°C to 40°C, whereas the collar rot infection appears most severe at 31°C to 35°C (Chohan, 1969).

#### 10.2.3.1.5 Moulds causing aflatoxin contamination

Aflatoxin contamination of groundnut is a major problem in most of the groundnut-producing regions across the world. The occurrence of drought during the late seed-filling period is a key contributing factor. It is caused by the growth of the moulds _Aspergillus flavus_ and/or _Aspergillus parasiticus_. Toxicity of groundnut from aflatoxin endangers the health of humans and animals and lowers market value (for example, Abdalla et al., 2005). Hence, it is a problem for groundnut producers as well as consumers. The moulds are common saprophytic fungi found in soils throughout the major groundnut-growing areas of the world (Pettit and Taber, 1973; Griffin and Garren, 1974). Pettit (1986) reviewed the influence of changing environmental conditions on the activity of the moulds affecting groundnuts. Aflatoxin is more serious during and following alternating dry and wet periods, namely, droughts following showers.

Pettit et al. (1971) observed that peanuts grown under dryland conditions and subjected to drought stress accumulated much more aflatoxin before digging than peanuts grown under irrigation. Wilson and Stansell (1983) reported that water stress during the last 40–75 days of the crop contributed to higher aflatoxin levels in mature kernels. Sanders et al. (1993) reported aflatoxin contamination in groundnut when pods were exposed to drought stress, although roots of the crop were well supplied with moisture. In a field study in Niger, Craufurd et al. (2006) confirmed that infection and aflatoxin concentration in peanut can be related to the occurrence of soil moisture stress during pod filling when soil temperatures are near optimal for _Aspergillus flavus_.

Cole and his colleagues (Cole et al., 1985, 1989; Dorner et al., 1989) have shown that pre-harvest contamination of aflatoxin requires a drought period of 30–50 days and a mean soil temperature
of 29°C–31°C in the podding zone. In Sudan, the irrigated region (central Sudan) used to be free from aflatoxins, while the rainfed region (western Sudan) showed high levels of aflatoxin contamination (Hag Elamin et al., 1988). In the same study, temperature of 30°C and relative humidity of 86 per cent were identified as optimum conditions for aflatoxin production. Rachaputi et al. (2002) observed aflatoxin contamination to be widespread in the Queensland region of Australia during the 1997–1998 seasons, with severe and prolonged end-of-season drought and associated elevated soil temperature; they observed lower aflatoxin risk during the 1999–2000 seasons, which featured well-distributed rainfall and lower soil temperatures.

10.2.3.2 Insect pests

Major insect pests in groundnut are: termites (Odontotermes), white grubs (Lachnosterna consanguinea), thrips, jassids (Empoasca kerri), aphids (Aphis craccivora), leaf miners (Aproaerema modicella), tobacco caterpillars and red hairy caterpillars (Amsacta albistriga). Environmental conditions are important factors in the survival, rate of development and fecundity of various crop pests.

10.2.3.2.1 Leaf miner

In the Anantapur region of southern India, leaf miners emerge during drought periods with no rainy days for more than 21 days between 35 and 110 days after sowing (Gadgil et al., 1999; Narahari Rao et al., 2000). Ranga Rao et al. (1997) also observed leaf miner infestation to be severe during moisture stress conditions. The conditions favourable for leaf miner growth are long dry spells resulting in high temperature and low humidity (Amin and Reddy, 1983). At Anantapur under late-sown conditions, the groundnut leaf miner incidence was significantly and negatively correlated with rainfall and minimum temperature and positively with sunshine hours (AICRPAM, 2001).

10.2.3.2.2 Heliothis armigera

*Heliothis armigera* (Hübner) has become a serious pest on groundnut in recent years. A study of the relationship between seasonal incidence of *Heliothis* and weather parameters (Upadhyay et al., 1989) showed that the *Heliothis* population was positively associated with maximum and minimum temperatures.

10.2.3.2.3 Aphids

Aphid distribution across a drought-stress gradient created by a long line-source overhead irrigation system (ICRISAT, 1989) showed that aphid density was much higher where most of the irrigation water had been applied and lowest at a point farthest from the water source, where plants were experiencing drought stress. Interestingly, rain falling on plants infected with aphids physically suppresses the aphids' population and a single heavy rainfall event can decrease their density by 90 per cent.

10.2.3.2.4 Red hairy caterpillars (Amsacta albistriga)

In the Anantapur region of India, a major groundnut growing region, emergence of red hairy caterpillar (RHC) was found to be closely related to heavy rainfall events (AICRPAM, 1997). The numbers of red hairy caterpillars reached a peak 3 to 4 days after a rain event and the outbreak of RHC could be predicted 8 to 9 days in advance. Red hairy and Bihar caterpillars appear after the onset of pre-monsoon showers in May/June (Padmavathamma et al., 2000).

10.2.3.2.5 Spodoptera litura

Under both laboratory and field studies at ICRISAT, Hyderabad, India, lower and upper threshold temperatures for development of *Spodoptera* in groundnut worked out to be 10.5°C and 30°C, respectively (Ranga Rao et al., 1989). The study also approximated the degree-day accumulation requirements for each stage of development of *Spodoptera*-like pre-oviposition females (30), eggs (55), larvae (315), pupae (155) and adult stages (generation time, 550).

10.2.4 Management aspects of groundnut in various environments

10.2.4.1 Protection measures

A history of leaf spot monitoring and forecasting and their increasing use in its control can be followed through the literature (Jensen and Boyle, 1966; Smith et al., 1974; Parvin et al., 1974; Phipps and Powell, 1984; Johnson et al., 1985; Smith, 1986). In 1989, a new advisory programme (89-ADV) that improved leaf spot control through better timing of fungicide sprays was released in Virginia (Cu and Phipps, 1993). This advisory programme was evaluated between 1990 and 1995. These evaluations showed that the programme saves on average three fungicide sprays per season, decreases input cost by 43 per cent and increases net returns by 26 per cent (about US$ 9 000 per year) compared with the previous programme.
An approach to providing advice for control of late leaf spots uses the number of days when rainfall exceeds a threshold (Davis et al., 1993). This was the basis for the AU-Pnut advisory developed to schedule initial and subsequent fungicide applications for control of early and late leaf spots. The AU-Pnut advisory uses the number of days with precipitation greater than 2.5 mm and the National Weather Service precipitation probabilities to predict periods favourable for the development of early and late leaf spots (Jacobi et al., 1995). The AU-Pnut advisory can be reduced to the number of leaf spot fungicide applications and achieve disease control and yield similar to that achieved with the 14-day spray schedule. AU-Pnut advisory II, a modified version of this advisory for partially resistant groundnut cultivars, saved 0.5 and 2.5 sprays per season compared with 21-day and 14-day schedules (Jacobi and Backman, 1995). At ICRISAT, India, Butler et al. (2000), using information from controlled-environment experiments on the response of leaf spots to temperature and leaf wetness periods, formulated a weather-based advisory scheme (WBAS) for control of leaf spots in groundnut. Bailey (1999) developed weather-based advisories using temperature and relative humidity for determining conditions favourable for early leaf spot development in North Carolina, United States. Johnson et al. (1999) used leaf wetness counting for predicting occurrence of late leaf spot in groundnut in the Anantapur region of India. In this study, application of fungicidal spray according to a leaf wetness index resulted in the highest net returns and cost–benefit ratio.

Ghewande and Nandagopal (1997), based on a research review of integrated pest management of groundnut in India, reported that intercrops of groundnut with pearl millet and soybean suppress the population of thrips, jassids and leaf miner. Intercrops with cassava suppress jassids and *Spodoptera*, while those with pigeon pea suppress early leaf spot, late leaf spot and rust. Wider row spacing of 50 × 30 cm and late-maturing and spreading-type varieties were found to be effective in reducing *Cercospora* leaf spot compared to narrow spacing (50 × 20 cm) and early-maturing and erect varieties under Nigerian conditions (Garba et al., 2005). Intercropping of groundnut with sorghum and pearl millet can reduce the incidence of *P. arachidis* (Reddy et al., 1991). Padmavathamamma et al. (2000) suggest the following management for controlling hairy caterpillars in groundnut: pre-monsoon deep ploughing to expose hibernating pupae to sunlight and predators; growing trap crops like cowpea, castor and jatropha on field bunds to trap and kill caterpillars; forming a deep furrow trench around the fields and dusting with 2 per cent methyl parathion to prevent mass migration of caterpillars. In Virginia, United States, an algorithm was developed to produce daily advisories for warning groundnut growers of the risk for *Sclerotinia* blight disease onset and the need for fungicide application (Phipps, 1995b). This algorithm uses environmental factors, such as RH and soil temperature, and the condition of the host plant, including vine growth and density of foliar canopy. Based on the success of this advisory programme in providing early warning conditions for disease onset at many locations, it was released to growers in 1996. In Georgia, United States, an algorithm was also developed for predicting outbreaks of *Sclerotinia* blight and improving the timing of fungicides to control it (Langston et al., 2002). In this algorithm, disease risk is calculated by multiplying indices of moisture, soil temperature, vine growth and canopy density each day. Algorithm-based sprayings have proven to be more efficient than the calendar-based sprays usually practiced.

The preceding steps are just examples of what is possible in combating groundnut crop blight and insect pests. Where farmers have successfully used these advisories, they are already examples of agrometeorological services. In Nigerian conditions, the significant relationship established between aflatoxin concentration and plant-extractable soil water (using the CROPGRW model) formed the basis for developing a decision support system to predict aflatoxin concentration in groundnut (Craufurd et al., 2006). Nageswara Rao et al. (2004) have used a similar approach to model the risk of contamination of aflatoxin in Queensland, Australia, using the Agricultural Production Systems Simulator (APSIM) crop simulation model; they have shown how farmers in Queensland can manage aflatoxin given a decision support system (DSS). In Queensland, Rachaputi et al. (2002) identified early harvest and threshing as best management practices for minimizing aflatoxin contamination under high aflatoxin risk conditions. In general, early sowing or early harvest and even supplementary irrigation (if available) are possible ameliorating practices for reducing the risk of aflatoxin.

10.2.4.2 Improvement measures

The paragraphs below provide some examples of management improvement issues. These are not in the form of any advice directed at farmers or decision support systems, however.

10.2.4.2.1 Sowing time

In Nigeria, when it is sown with early rains, the crop invariably takes advantage of higher solar radiation and warmer temperatures to become well
established. According to Kowal and Knabe (1972), the optimum time to begin cropping with little or no drought risk in Nigerian conditions may be defined in terms of latitude (X) and expressed by the equation $Y = 1.43X - 1.31$, where $Y$ represents days in dekads (10-day periods). In India, sowing of rainfed and irrigated crop early in the season provided favourable weather conditions for proper growth and yield of groundnut. Delay in sowing by one week from 17 July to 24 July resulted in a linear decrease in pod yield of groundnut (Murthy and Rao 1986). In a crop sown at the normal time (first week of July), the pattern of flowering is regular with two distinct peaks of flowering, whereas in a late-sown crop (end of July), an erratic pattern of flowering occurs. In southern parts of India, November is the best period for sowing the rabi crop raised on residual soil moisture, and sowing between December and the end of January is most suitable for obtaining higher yields in irrigated summer crops.

### 10.2.4.2.2 Varietal selection

The choice of a groundnut variety for any particular area depends on matching the variety with the length of the growing season. Groundnut varieties whose growth cycle is longer than the duration of the growing season at a particular location either fail to mature or mature at a time when the soil is too hard to dig the pods. In a majority of the groundnut-growing regions, drought stress affects groundnut production. Under Indian conditions, ICGV 86699, K-134 and TMV-2 were considered drought-tolerant (Reddy and Setty, 1995). Ali and Malik (1992) reported that ICGS (E) S2 and ICGS (E) 56 were promising short-duration varieties that could escape end-of-season drought in rainfed areas of Pakistan. Schilling and Misari (1992) reported that short-duration and erect varieties like 55-437, released in Cameroon, Chad, Gambia, Niger and Nigeria; varieties 73-30 and 73-73, released in West Africa; and ICGS (E) 30 and ICGS (E) 60, released in Botswana, are drought-tolerant.

### 10.2.4.2.3 Plant population

The optimum population of groundnut differs with genotype. A short-duration Spanish cultivar, McCullin, showed yield response up to 40 000 plants ha$^{-1}$. The optimum population for Spanish bunch varieties under rainfed conditions in India is 33 000 plants ha$^{-1}$ (NARP, 1992). Crops grown on residual soil moisture should be planted at lower populations than those grown during rainy seasons. An analysis of data drawn from across the main groundnut-growing areas of Nigeria indicates substantial increases in plant population from the currently advised population of 47 000 plants ha$^{-1}$ for yield benefits (Yayock and Owonubi, 1983).

#### 10.2.4.2.4 Scheduling and methods of irrigation

Maintenance of optimum soil moisture at critical growth stages is the key factor in achieving higher yields. Peak flowering and pod formation stages are more critical stages. After adequate germination moisture is provided through irrigation, a “drought” is imposed by withholding irrigation for 20 days, and relief from the water stress is provided by two irrigations at an interval of five days. This method helps in the development of a deeper root system, synchronized flowering, higher biomass production and higher pod yield (Ghosh et al., 2005). The ratio of irrigation water and cumulative pan evaporation (IW/CPE) for groundnut ranges from 0.6 to 1.0. Ramachandrappa et al. (1993) reported that irrigation should be scheduled at 0.5 IW/CPE during the period 10–40 days after sowing and later on at 0.75 IW/CPE to realize higher pod yields. In the sandy loams to sandy clay loam soils of eastern India, 4 cm of water at 0.9 IW/CPE or 4 cm of water at a 7-day interval are suitable levels of irrigation for growing groundnut (Das, 2004).

The furrow method of irrigation is the most effective with maximum water use efficiency of 3.71 kg ha$^{-1}$ mm$^{-1}$; it also saves 2–3 irrigations compared with the border strip and check basin methods (Kathmale and Chavan, 1996). The use of sprinkler and drip irrigation methods is becoming popular since the water requirement in these methods is about half of other irrigation methods, and water use efficiency is high. A yield advantage of 32 per cent over the check basin method was realized with a sprinkler irrigation system (Devi Dayal et al., 1989). Besides a 24.7 per cent savings of irrigation water, the groundnut yield under sprinkler irrigation was 18.8 per cent higher than the yield obtained under surface irrigation (CPRWM, 1984). In the Konkan region of Maharashtra, India, sprinkler irrigation increased pod yields by 20.8 per cent and resulted in a 33 per cent saving of irrigation water compared with the check basin method (Kakde et al., 1989). In the United States, groundnut yields with surface drip irrigation were 1.43 times the non-irrigated yield. The yield gain from surface drip irrigation was 10 kg ha$^{-1}$ mm$^{-1}$ (Zhu et al., 2003). At Ludhiana, India, among the different irrigation systems, a trickle irrigation system showed a yield increase of 21 and 11 per cent over conventional and micro-sprinkler irrigation systems, respectively; for summer-planted bunch groundnut cv SG-84 (Narda et al., 2003). Sorensen et al. (2004) reported results of subsurface drip irrigation in the United States.
10.2.4.2.5 Mulching

In dryland conditions, traditional practices like contour cultivation in a sloping field, soil mulching, intercultivation and weed control help conserve soil moisture in groundnuts (WMO, 1988). In Rajasthan, Uttar Pradesh, Orissa and West Bengal in India, low soil temperature during the rabi season delays germination and high temperature at the pod-filling stage interferes with pod development.

Research conducted at the National Research Centre for Groundnut, Junagadh, India, showed that application of chopped wheat straw at 5 t ha\(^{-1}\) on the soil surface immediately after sowing of groundnut raised soil temperature by 2°C–3°C at seedling emergence and lowered soil temperature by 3°C–5°C during the pod development phase. Under wheat straw mulch, the groundnut crop thus maintained good vigour and growth and gave a yield 20–24 per cent higher than the control (Ghosh et al., 1997). De et al. (2005) found that water hyacinth mulch conserved more soil moisture, maintaining low soil temperatures at soil depth and manifesting higher kernel yield in summer groundnut sown under rainfed conditions in West Bengal, India.

10.2.4.2.6 Sowing methods

In high rainfall areas with deep vertisols, broad bed and furrow methods of sowing were found to be more effective than other methods. On average, use of the broad bed and furrow system resulted in a groundnut yield that was 15 per cent higher than the yield from the flat bed method (ICRISAT, 1993). Similarly, in summer-sown groundnut under rainfed conditions of West Bengal, India, the ridge planting method not only maintained slightly higher soil moisture (8.4 per cent) compared with the flat planting method (7.3 per cent), but also produced higher kernel yield of groundnut (0.57 t ha\(^{-1}\)) than flat planting (0.42 t ha\(^{-1}\)) (De et al., 2005).

10.2.4.2.7 Shelterbelts

In drylands of northern China, data spanning 40 years on agri-silvicultural practices with trees, shrubs and woody plants (used as windbreaks) that were planted in combination with groundnut crops showed a groundnut yield increase of between 5.8 and 12.8 per cent due to the windbreaks or shelter belts (Qi and Tishoon, 2004). A similar study by the Australian Government Rural Industries Research and Development Corporation suggested that incorporation of windbreaks in groundnut farming systems in the Atherton tablelands of Australia increased groundnut yield by an average of about 12 per cent compared to the control.

10.2.5 User requirements for agrometeorological information on groundnut

Up-to-date services of accurate weather data can be an important decision-making aid for all segments of the groundnut industry. In groundnut-growing areas of the United States, before planting crops in the spring, growers routinely check soil temperature and weather forecasts to determine when conditions are favourable for seed germination and emergence of the crop. Groundnut seed should be planted in soils that reach 18°C or higher temperatures at 5 to 10 cm depth each day and when forecasts indicate that these conditions are likely to continue over the next 3 to 5 days.

Growers are also interested in reports of accumulated heat units and rainfall. These data are widely used to gauge the progress of crop development and to forecast the maturity date and yield potential of groundnut. In the Anantapur region of southern India, it was observed from long-term research on groundnut that rainfall of 500 mm was required to sustain a successful groundnut crop. Hence a prediction of seasonal rainfall of 500 mm is useful for groundnut growers in this region. As seasonal rainfalls of less than 500 mm are related to El Niño years, a prediction for El Niño has a potential for application in farm-level decisions in this region (Subbiah and Kishore, 2001).

Growers want accurate long-range weather forecasts with finer spatial and temporal scales for agricultural management applications, such as selection of varieties, choice of intercropping, increasing or decreasing the area to be planted, soil and water conservation techniques, and so forth. During the course of the crop-growing season, certain midterm corrections will be required to minimize yield losses. Hence, medium-range forecasts covering 5 to 7 days will provide critical information for undertaking corrective measures. Accurate short-range forecasts for weather aberrations like frost, hailstorms, and so forth should be made available to users. In Virginia, United States, a groundnut frost advisory programme uses separate algorithms to adapt the 7-day low temperature forecast to each regional site in the groundnut production areas (Phipps et al., 1997). Such types of advisories need to be made available in other regions that have a frost risk.

In the Gambia, farmers store groundnuts in heaps in open air for three months until a government agent

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visits. During this time, the groundnut harvest is vulnerable to rain. Short-range rainfall forecasts would facilitate the protection of stored groundnuts by warning the farmers against impending rain (Kuisma, 1995). The value of one single good forecast for impending rain (even if only 10 per cent of the harvest is saved) would be US$ 600 000. The weather-based advisories for making disease management decisions and weather monitoring networks available in United States should be extended to other groundnut-growing areas of the world.

In semi-arid areas, soil water balance affects almost all stages of production of the groundnut crop. Decision support systems based on real-time weather conditions, means of identifying moisture stress due to early or midseason dry spells and adaptation options suited to the circumstances need to be developed in semi-arid and arid regions. Developments in information technology have to be used in groundnut-growing areas for quick and cost-effective dissemination of weather-based agricultural advisories to growers. Chapter 1 and Stigter (2006a) discuss the initial and boundary conditions for such developments. Chapter 17 reviews communication of agroclimatological information.

In three south-eastern United States counties – Henry (Alabama), Jackson (Florida) and Mitchell (Georgia) – Fraisse et al. (2004) explored the use of crop growth simulation models in combination with climate forecasts to decide insurance coverage levels for groundnut producers. In Malawi, the World Bank drought index insurance seems to have been accepted by groundnut farmers, lenders and insurers as the best way for management of drought risk (http://www.microinsurancecentre.org). In Andhra Pradesh, India, rainfall insurance for payment of insurance compensation to (rainfed) groundnut farmers was implemented by ICICI (Lombard) Bank on the basis of a rainfall index. Weights were used for constructing a groundnut index in accordance with the commencement of the rainy season and period of sowing. Farmers receive payment if the index level falls below a predetermined threshold. Despite some problems, groundnut farmers are opting for this rainfall-based insurance scheme.

10.2.6 **Agrometeorological services for groundnut**

Operational decision support systems increase profit for groundnut growers. Groundnut yield, quality, and net farm income depend on optimum and timely management. Scientists from the Agricultural Research Service at the National Peanut Research Laboratory (NPRL) operated by the United States Department of Agriculture in Dawson, Georgia, have developed and released, through a Cooperative Research and Development Agreement with the Peanut Foundation, an integrated decision support system (Farm Suite Version 2.0). This includes computer software for the management of irrigated groundnut production (Irrigator Pro), harvesting (Harv Pro), capital investment service (CIS), sprinkler operation and ownership costs, and curing (PECMAN). Over 100 copies of the software have been distributed as shareware to growers, extension agents and crop consultants throughout the groundnut-growing regions of the United States. Producers from New Mexico to Virginia using Farm Suite have optimized irrigation, pesticide applications and other production factors. Use of this decision aid tool not only increased groundnut yields by about 336 kg/ha but also improved the grade of harvests, decreased aflatoxin contamination and increased profits (US$ 741 per ha) by comparison with the average groundnut grower.

The Website of the Southeast Climate Consortium (http://www.agroclimate.org) provides decision support tools such as groundnut outlook, yield risk analysis, management options and crop insurance for groundnut-growing states in the south-eastern United States. Another service is the Mesoscale Atmospheric Simulation System (MASS), which was used to predict hourly weather information 48 hours in advance for one-square-kilometre pixels at the geographic centre of two counties, Bertie and Gates, in North Carolina (http://cipm.ncsu.edu/cipm projects).

Water balance/stress index models are applied rather routinely in West African countries for agrometeorological and food security assignment – groundnut is also one of the target crops. The creation of a regional Agrhymet centre on agrometeorological services in the Sahelian countries has provided solutions to some problems. This includes continuing earlier pilot projects for assistance to the rural population in Mali, where farmers have received and applied advice from the Multidisciplinary Working Group for Agrometeorological Assistance (GTPA) in the course of the rainy season (for example, Stigter, 2006b).

In Sudan, Ibrahim et al. (2002) did on-farm quantitative work on water waste in the Gezira irrigation scheme as an agrometeorological service to tenants and administrators, with the aim of assisting in the development of better local water use efficiency policies. They compared less labour-intensive groundnut irrigation methods, adopted because of
the necessity of working with sharecroppers who also had off-farm employment, to traditional modes of irrigation that were more labour-intensive and had been abandoned over time. They found that there was water waste in both methods of irrigation, but much more in the unattended fields and in the drier year of the two growing seasons investigated. In that year, the water waste was 50 per cent of the minimum water requirements determined. This did not yet include the readily available water still retained in the soil profile at the end of each growing season. Contrary to sorghum, the groundnuts also suffered from excess water.

For China, Stigter et al. (2006) reported that traditional farmers had recently used contour native grass belts for erosion reduction, in rotation with tilling the land for growing groundnuts for income and sweet potatoes for animals. Farmers appear to have obtained the innovative knowledge from a disaster in which erosion caused by very heavy rain seriously damaged corn-based cropping systems on hilly sandy soil, while narrow plots of groundnut between native grasses escaped the disaster. These contour belts are 2 m wide and the grasses are cut to feed working cattle. Local applied research would be able to improve these farmer-developed systems, leading to better agrometeorological services through design rules.

10.3 AGROMETEOROLOGY AND MAIZE PRODUCTION

10.3.1 Importance of maize in various climates

Maize is the world’s third most important crop after rice and wheat. About half of this is grown in developing countries, where maize flour is a staple food for poor people and maize stalks provide dry-season feed for farm animals. Diversified uses of maize worldwide include: maize grain; starch products; corn oil; baby foods; popcorn; maize-based food items; maize flour; forage for animals; maize stalks providing dry-season feed for farm animals; maize silage for winter animal feed in cold temperate regions; and maize stalks as a soil mulch where it is in abundance. Maize grain is used as feed for beef, dairy, hog and poultry operations in developed countries. Maize can be classified on the basis of its protein content and hardness of the kernel. Varieties include popcorn and flint, flour, Indian and sweet corn.

In industrialized countries maize is largely used as livestock feed and as raw material for industrial products; for instance, in Australia it is used for feed, silage, breakfast food and processing (breakfast cereals, corn chips, grits and flour), industrial starch and popcorn. In low-income countries it is mainly used for human consumption.

In sub-Saharan Africa, maize is a staple food for an estimated 50 per cent of the population and provides 50 per cent of the basic calories. It is an important source of carbohydrate, protein, iron, vitamin B and minerals. Africans consume maize as a starchy base in a wide variety of porridges, pastes, grits and beer. Green maize (fresh on the cob) is eaten parched, baked, roasted or boiled and plays an important role in filling the hunger gap after the dry season. The yields are low, however, fluctuating around 1.0 tonne per hectare (t/ha). Several African countries have focused attention on increasing maize production in the smallholding agricultural sectors, but such efforts have been ineffective because of heavy pre- and post-harvest losses caused by diseases, weeds and pests. In South Africa, in addition to the traditional uses, the country is considering maize fuel, an alcohol-based alternative fuel produced by fermenting and distilling the starch-rich grains of the crop.

According to United Nations Food and Agriculture Organization (FAO), maize yields currently average 1.5 t/ha in Africa, slightly more than 3 t/ha in Latin America and 1.7 t/ha in India. FAO indicates that grain yields have been recorded as follows: 5–6 t/ha (dryland) and 8–10 t/ha (irrigated). For silage, at 68–70 per cent moisture content, yields of 20 t/ha (dryland) and 42 t/ha (irrigated) have been recorded.

10.3.1.1 Importance of maize in the United States

Maize grain yields have exceeded 12.5 t/ha in the United States and in southern Ontario, Canada, without irrigation, and the value of this crop now exceeds US$ 20 billion in North America. Corn refineries use 14 per cent of the United States maize crop, manufacturing such products as: corn oil; gluten for animal feed; corn starch; corn syrup; dextrose (used mainly by the pharmaceutical industry as the starting material for manufacturing vitamin C and penicillin); alcohol for beverages; bioethanol (which accounts for 12 per cent of all automobile fuels sold in the United States); high-fructose corn syrup (used mainly by the soft drink industry, surpassing the use of sucrose in the United States); biodegradable chemicals and plastics; paper; textiles; ready-to-eat snack foods and breakfast cereals; cornmeal grits; flour; and additives in paint and explosives. It is estimated that maize yields
4,000 industrial products and that there are more than 1,000 items in United States supermarkets that contain maize.

### 10.3.1.2 Yield gap and yield potential

In the developing world, most farmers have to accept low yields, as they are unable to consider the use of improved production methods because they operate at small-scale subsistence levels. Yield gap analyses will draw farmers’ attention to lost production potential under the prevailing climatic conditions in their respective environments and which production practices (soil fertility, agronomic measures, cultivar selection, and the like) need to be improved. Yield differences among regions as shown in Table 10.3.1 should provide the incentive to manoeuvre toward yield improvement. (Yield potential refers to the highest yield achievable on farmers’ fields – with the use of improved seed (high yield, tolerance to diseases and pests), appropriate levels of nutrients, water and weed control.)

According to Ofori et al. (2004), the difference between the actual and potential yield of a typical maize variety grown during the major cropping season (April through July) on a farm in Ghana over a nine-year period was just over 4 t/ha (that is, the actual yield varied from 0.9 to 1.4 t/ha and the potential for that season should have been 5.5 t/ha). The April–July rainfall varied from 570 to 790 mm over this nine-year period.

### 10.3.1.3 Maize production profile by region in the developing world

In the tropics and subtropics, small-scale farmers grow most of the maize, generally for subsistence as part of agricultural systems that feature several crops and sometimes livestock production. The system often lacks inputs such as fertilizer, improved seed, irrigation and labour. In most developing countries there is very little purchased input for the cropping system and it essentially depends on the natural resource base. The soil nutrients in the natural resource base are dwindling faster than they are being replaced. Rainfall is the single most important natural resource input under this form of cropping. Increasing population pressure has resulted in an intensification of land use. Nutrients and organic matter in the soil have been depleted and crop yields have steadily decreased. To increase production it will be necessary to replenish soil nutrients and optimize the use of other resources such as seed, water, capital and labour. Land-use intensification is only feasible if nutrients depleted during cultivation are replenished. Inorganic fertilizer use in sub-Saharan Africa is generally limited by the lack of financial resources for the farmers. Table 10.3.2 shows the dominant constraints to bridging the gap between the actual and potential yield in the developing world.

Most maize-producing countries in the industrialized world employ extensive inputs and highly mechanized crop production systems; these countries commonly use hybrid maize seed.

### 10.3.2 Agroclimatology of the crop

Climate is interrelated with other production factors and should be understood either as a resource to be managed or a factor that needs to be manipulated. Sustainable use of soil, capital and labour should be balanced with use of climate and weather information.

The response of the maize crop to climate depends on the physiological makeup of the hybrid/variety being grown. Yield differences are the result of the genetic composition of the hybrid, the environmental conditions under which the crop is grown, and the infestation by crop pests (diseases, insects and weeds). The final yield will depend on hybrid selection, soil fertility, soil water and control of

#### Table 10.3.1. Yield potential (t/ha) relative to (current yield) in developing world (Prabhu et al., 2000)

<table>
<thead>
<tr>
<th>Ecological environment</th>
<th>Highland/transitional</th>
<th>Mid-altitude/subtropical</th>
<th>Tropical/lowland</th>
</tr>
</thead>
<tbody>
<tr>
<td>East and South-East Asia</td>
<td>5.0 (3.5)</td>
<td>8.0 (3.0)</td>
<td>5.5 (2.2)</td>
</tr>
<tr>
<td>South Asia</td>
<td>5.0 (0.7)</td>
<td>7.0 (2.6)</td>
<td>4.5 (1.4)</td>
</tr>
<tr>
<td>West Asia/North Africa</td>
<td></td>
<td>4.5 (3.2)</td>
<td></td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>5.0 (0.6)</td>
<td>7.0 (2.5)</td>
<td>4.5 (0.7)</td>
</tr>
<tr>
<td>Latin America and Caribbean</td>
<td>6.0 (1.1)</td>
<td>10.0 (4.0)</td>
<td>5.0 (1.5)</td>
</tr>
</tbody>
</table>
crop pests. These factors will be discussed in this order.

Each farmer has to select the hybrids that are most suitable for the climatic region in which his or her farm is located. In temperate regions of the world, the length of the frost-free season dictates the hybrids that are suitable, because the maize plant cannot withstand temperatures below about –2°C. Growing degree-day and heat-unit indexing systems have been developed for most temperate regions of the world, so that the maturing time required by each maize hybrid can be matched with growing degree-day or heat-unit ratings for the frost-free growing season in each climatic region. In tropical regions of the world it is the rainy season onset that dictates the selection and optimum time to plant maize hybrids. They need to be selected to match the anthesis period to the time that the soil moisture is likely to be most adequate, unless there is water available to irrigate the crop when necessary.

The soil fertility needs to have an optimum balance of the three major nutrients, which are nitrogen,

Table 10.3.2. Dominant constraints to bridging the yield gap between potential and actual yields in the developing world (Bellon, 2001)

<table>
<thead>
<tr>
<th>Ecological environment</th>
<th>Highland/transitional</th>
<th>Mid-altitude/subtropical</th>
<th>Tropical/lowland</th>
</tr>
</thead>
<tbody>
<tr>
<td>East and South-East Asia</td>
<td>(a) Limited technological options</td>
<td>(a) Drought/moisture stress</td>
<td>(a) Limited superior early germplasm</td>
</tr>
<tr>
<td></td>
<td>(b) Banded leaf and sheath blight</td>
<td>(b) Soil acidity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(c) Borers (<em>Chilo</em> spp.)</td>
<td>(c) Downy mildew</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(d) Borers (<em>Chilo, Sesamia</em> spp.)</td>
<td>(d) Borers (<em>Chilo, Sesamia</em> spp.)</td>
<td></td>
</tr>
<tr>
<td>South Asia</td>
<td>(a) Low and declining soil fertility</td>
<td>(a) High temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(b) Limited technological options</td>
<td>(b) Drought/moisture stress</td>
<td></td>
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<tr>
<td></td>
<td>(c) Turcicum blight</td>
<td>(c) Drought/moisture stress</td>
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<td></td>
<td></td>
<td>(d) Borers (<em>Chilo, Sesamia</em> spp.)</td>
<td></td>
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<tr>
<td>West Asia/North Africa</td>
<td>(a) High temperature</td>
<td>(a) Limited superior early germplasm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(b) Drought/moisture stress</td>
<td>(b) High temperature</td>
<td></td>
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<tr>
<td></td>
<td>(a) Low and declining soil fertility</td>
<td>(c) Downy mildew</td>
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<td></td>
<td>(b) Limited technological options</td>
<td>(d) Downy mildew</td>
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<td></td>
<td>(c) Turcicum blight</td>
<td>(e) Borers (<em>Chilo, Sesamia</em> spp.)</td>
<td></td>
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<tr>
<td></td>
<td>(d) Rust</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>(a) Low and declining soil fertility</td>
<td>(a) Low and declining soil fertility</td>
<td></td>
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<td></td>
<td>(b) Limited technological options</td>
<td>(b) Drought/moisture stress</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(c) Turcicum blight</td>
<td>(c) Striga</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(d) Rust</td>
<td>(d) Streak virus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(e) Borers (<em>Chilo, Sesamia</em> spp.)</td>
<td>(e) Borers</td>
<td></td>
</tr>
<tr>
<td>Latin America and Caribbean</td>
<td>(a) Limited technological options</td>
<td>(a) Soil erosion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(b) Drought/moisture stress</td>
<td>(b) Drought/moisture stress</td>
<td></td>
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<td></td>
<td>(c) Ear rot</td>
<td>(c) Drought/moisture stress</td>
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<td></td>
<td>(d) Rust</td>
<td>(d) Fall armyworm</td>
<td></td>
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<td></td>
<td></td>
<td>(e) Stunt</td>
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</tbody>
</table>
phosphorus and potassium, and the necessary micro-nutrients, such as boron, calcium, magnesium, manganese and molybdenum. The farmer should have the soils on his or her farm assessed for the three major nutrients every year or two to determine how much fertilizer should be added to maximize maize production. This is an important management practice in both temperate and tropical regions. The farmer should be aware of fertilization requirements and procedures with respect to the soil nutrient levels, the growth stage, the crop variety, the targeted yield and the agronomic practices.

In order to maximize maize yields, soil moisture should be maintained above 50 per cent of the available water capacity in the rooting depth of the soil profile throughout the growing season. This is not always possible in either temperate or tropical climatic regions as rainfall can be very scarce and sporadic in some years. It is essential, however, to have at least adequate soil moisture at the time of anthesis in order to have a full set of kernels on the ear at harvest time. This is the time when supplemental water through irrigation would be most beneficial.

Crop infection and infestation by diseases, insects and weeds can significantly reduce yields in both temperate and tropical regions, and agronomology is important in crop protection. Diseases are best controlled through maize breeding programmes that develop hybrids with resistance to such diseases as leaf blights (of which Bipolaris, Colletotrichum and Excesohilium strains are common examples); root and stalk rots (of which Phytophthora, Fusarium, Gibberella and Diplodia strains are representative cases); rusts (including Puccinia and Polyspora); and smuts (such as Ustilago and Sphacelotheca strains). Maize diseases are usually not controlled by spraying with fungicide chemicals, except that seed is often treated before planting with a fungicide powder to control soil pathogens that damage the embryo before germination. (These fungi include the Pythium, Fusarium, Diplodia, Rhizoctonia and Penicillium species.) Wet and cold soil conditions (<10°C) at planting time are most favourable for these seed diseases.

The problem of disease and pest control among different production levels is particularly acute in the small-scale, resource-poor systems under which maize is typically grown in tropical regions of the world. The most inexpensive control measure for insects is crop rotation, which ensures that maize is not grown on the same land year after year.

Numerous species of weeds can infest maize crops and cause yield losses in both temperate and tropical regions. The Amaranthus, Panicum and Butillon species are the most detrimental in temperate regions, while the Striga species have the greatest impact in tropical regions, especially in Africa. Among the 23 Striga species in Africa, Striga hermonthisca is the most detrimental. In temperate regions, most of the time weeds are controlled by herbicide application. Since these chemicals are applied shortly after planting maize, when the soil needs to be moist but not too wet, weather conditions play a major role in the success of weed control in temperate climates. Some weed species have developed strains resistant to the “triazine” chemicals that are usually applied before emergence of maize seedlings, so it is sometimes necessary to apply alternative herbicides after emergence. Herbicides are often too expensive for farmers to use in tropical regions, so other cultural practices, such as crop rotation and hand cultivation, are used to control weed infestations.

Weather conditions play a role here too, but are not as critical as they are in herbicide application. According to several studies around the world (James et al., 2000; OMAFRA, 2002; Dogan, 2003) the best time to minimize the effect of weeds on maize yields is within 4 to 8 weeks after planting, when maize is in the 2- to 8-leaf stage. When weeds are controlled culturally during this initial period of maize growth, shading by the crop is quite effective in controlling weed growth during the remaining time to maturity.

10.3.3 Basic management aspects of the crop in various environments

Promotion of growth and yield will mean that an effort has to be made to reduce the effects of pests, diseases, drought and frost, which cause crop losses for both commercial farmers and smallholder, resource-poor farmers.

Drought stress alone can account for a significant percentage of average yield losses and is one of the greatest yield-reducing factors in production. There are two facets to drought resistance in maize:

(a) Affordability of irrigation systems. Not all farmers have access to irrigation systems and the cost of these systems limits their use by resource-poor farmers;

(b) Increasing pressure on water resources from other user sectors. As water resources for agronomic uses become more limited, the development of drought-tolerant varieties becomes increasingly more important (Wesley et al., 2001).

Apart from breeding and soil management, drought control measures include:

(a) Timing of planting to coincide with the time of adequate soil moisture availability based
on the availability and user appreciation of agrometeorological information;
(b) Reduction of plant population with moisture scarcity (thinning);
(c) Higher soil fertility to increase plant health and improve resistance to diseases and pests;
(d) Weed control to reduce competition for water between the maize plant and the weeds. Weed control also creates suitable humidity levels for the maize plant environment.

There are considerable research efforts at both regional and international levels in developed and developing countries that are aimed at providing drought-resistant hybrids. Plant breeding and biotechnology can offer some flexibility in drought management for rainfed or dryland maize production. What is important is to characterize the hybrids according to their level of tolerance to allow for easy selection by farmers or farmer groups. Drought-resistant hybrids and their composites are often more promising in dryland environments than local maize varieties (Obeng-Antwi et al., 2002).

As a result of the warming and changing climate patterns, maize yield is going to be reduced, especially among smallholder maize farmers, who may lack the resources to cope with these situations. With the effect of climate change resulting in reduced rainfall amounts and increased soil and plant evapotranspiration, one important goal is to enhance drought resistance in maize and other cereal crops, which would greatly benefit regions with less favourable conditions for agriculture. Solutions must go beyond increasing production, as boosting the nutrient content of the maize is important as well. Breeding of high-yielding, high-nutrient varieties with limited water use could provide part of the answer.

It is clear that climate influences the incidence of pests, diseases and weeds, though the intensity of these effects differs among crops and regions depending on climatic conditions, crop resistance and crop management, which may include cultivation techniques, such as fertilization, water supply and crop protection. Protection measures should be targeted at managing weeds, pests and diseases. Can control be put within the reach of resource-poor farmers?

Weed control for yield increase can be quite costly to resource-poor farmers. Part of the solution lies in the use of biodiversity and biotechnology. To put stem borer and Striga control within the reach of African farmers, simple, inexpensive measures need to be developed that are tailored to the diversity of African cropping and socio-economic systems. A sustainable solution would be an integrated approach that simultaneously addresses disease, pests and weeds.

Ndema et al. (2002) reported on weed grasses grown as trap plants in border rows around maize plots, which led to reduced pest densities in maize. This was due to an increase in plant-induced mortality occurring on grass species in both the humid forest and the derived savanna of western Africa. Yields per plant tended to be higher when grasses were present, with the highest increase of >100 per cent observed in Cameroon in the second year of the experiment, when the grasses were well established. The most promising grass species identified in the study were Pennisetum purpureum and Panicum maximum. The latter was the most efficient species for suppressing S. calamistis and M. nigrivenella infestations and enhancing egg and larval parasitism.

The new approaches utilize the benefits of biodiversity of graminous and leguminous plants in the cultivation of maize; how to manage these plants in order to reduce stem borer and Striga infestation and increase stem borer parasitization by natural enemies in cereal cropping systems has been demonstrated. The approaches rely on enriching the biodiversity of plants and the pests’ natural enemies in and around the cropping environment. Based on an understanding of the volatile semiochemicals employed by the stem borers in locating suitable hosts and avoiding non-hosts, a novel pest management approach utilizing a “push–pull” or stimulo-deterrent diversionary strategy has been developed. In this habitat management system, which involves combined use of trap and repellent plants, insects are repelled from the main crop and are simultaneously attracted to a discard or trap crop. For maximum efficiency, these systems also exploit natural enemies, particularly parasitic wasps, which are important in suppressing pest populations. Plants that repel stem borers and also inhibit Striga weed have been identified as well.

Several plants have been identified that could be used as trap or repellent plants in a push–pull strategy, according to the study. Particularly promising are Napier grass (Pennisetum purpureum), Sudan grass (Sorghum vulgare sudanense), molasses grass (Melinis minutiflora) and the legume silverleaf (Desmodium uncinatum). Napier grass and Sudan grass have shown potential for use as trap plants, whereas molasses grass and silverleaf repel ovipositing stem borers. All four plant species are of economic importance to farmers in Africa as livestock fodder and have shown great potential for stem borer and Striga control in on-farm
trials. Napier grass, a commercial fodder grass, can provide natural control on stem borers by acting as a trap plant, and as a reservoir for their natural enemies. Napier grass has its own defence mechanism against crop borers. When the larvae enter the stem, the plant produces a gum-like substance, which causes the death of the pest.

Sudan grass, also a commercial fodder grass, can provide natural control by acting as a trap plant for stem borers and as a reservoir for their natural enemies. Planting Sudan grass around maize fields reduced stem borer infestation on maize and also increased efficiency of natural enemies (Khan et al., 1997a). Molasses grass, when intercropped with maize, not only reduced infestation of maize by stem borers but also increased parasitism, particularly by the native larval parasitoid Cotesia sesamiae (Khan et al., 1997b). The plant releases volatiles that repel stem borers, but attract parasitoids that cause no damage to the plants. Such plants with an inherent ability to release such stimuli could be used in ecologically sound crop protection strategies.

Molasses grass, which originated in Africa but spread to other tropical areas in the world, is well known to be a valuable pasture and hay grass. The grass also has high anti-tick properties, especially when green. The grass is familiar to farmers in eastern Africa and is reported to be preferred as fodder for both dairy and beef cattle. Silverleaf, a high-value, commercial fodder legume, when intercropped with maize, repelled ovipositing gravid stem borer females, and suppressed Striga by a factor of more than 40.

The habitat management strategy manifests important features that render it markedly more advantageous than other methods. The first of these features is its suitability to conditions of mixed agriculture, which is prevalent in eastern Africa. The cultivation of the grasses and legumes can increase both crop yield and livestock productivity. A second key feature of the proposed technology is that it introduces practices that are already familiar to farmers in Africa. The approach uses multiple cropping, and it is based on the use of economically valuable plants. For example, the cultivation of Napier grass for livestock fodder and soil conservation, recommended in eastern Africa, is already widespread.

10.3.4 Other background information on the crop

10.3.4.1 Growth stage monitoring

The maize plant described in Table 10.3.3 is representative of a lowland tropical variety, flowering in 55–60 days and maturing in 115 days. Considerable variation exists among varieties in terms of morphology and growth habit, however. For example, an early-maturing tropical variety may reach a height of only 1.5 m, flowering in 45–50 days and maturing in 90 days. Growth stages in the pattern shown in Table 10.3.3 should be prepared as a management guide. It must be emphasized that environmental factors influence the length of the various growth stages and for this reason information about the environmental factors should also be part of the characterization. Familiarity with the names and locations of the plant parts is helpful in understanding how the plant develops.

Table 10.3.3 gives the approximate number of days after sowing in the lowland tropics where maximum and minimum temperatures may be 33°C and 22°C, respectively. In cooler environments, these times are extended. For each variety a phenological characterization such as this can be useful. Planting dates should be such as to avoid exposure to increased risk of plant diseases, pests and soil moisture stresses.

10.3.4.2 Growth monitoring – an illustration

All normal maize plants follow this same general pattern of development, but the specific time interval between stages and total leaf numbers developed may vary among different locations, hybrids, seasons and planting dates. For example:

(a) An early-maturing hybrid may develop fewer leaves or progress through different stages at a faster rate than indicated here (Table 10.3.3). A late-maturing hybrid may develop more leaves or progress more slowly than indicated, however;
(b) The rate of plant development for any hybrid is directly related to temperature, so the length of time between the different stages will vary as the temperature varies, both between and within growing seasons;
(c) Environmental stress, such as nutrient or moisture deficiencies, may lengthen the time of vegetative stages but shorten the time between reproductive stages;
(d) The number of kernels that develop, final kernel size, rate of increase in kernel weight and length of the reproductive growth period will vary among hybrids and environmental conditions.

10.3.4.3 Biotechnology

It is expected that the use of biotechnology in the improvement of maize production will mean
collaboration between other disciplines and agrometeorologists. This should facilitate the development of suitable maize varieties for drought resistance and improved tolerance, as well as for low nitrogen availability, which occurs in most developing countries under rainfed production. The development of maize that is resistant to pests, diseases and weeds, as well as maize varieties with increased starch and protein contents, should be a feature of biotechnology advances. The direction of such biotechnology endeavours depends on regional production goals. Is production aimed at poverty alleviation, biofuel or increased protein content? Many questions of this kind may be asked.

Genetic engineering offers new possibilities for plant breeding for increased resistance to pests and pathogens, as well as other traits. New varieties resistant to pests, diseases and weeds, as well as maize varieties with increased starch and protein contents, should be a feature of biotechnology advances. The direction of such biotechnology endeavours depends on regional production goals. Is production aimed at poverty alleviation, biofuel or increased protein content? Many questions of this kind may be asked.

Under different climatic conditions and environments, varietal selection has to be based on a host of factors, for example, whether the crop is produced under rainfed/dryland conditions, unimodal or bimodal rainfall patterns, supplementary or fully irrigated systems or under sufficient or limited rainfall conditions.

### 10.3.5 Some management details

Agronomic practices that will improve soil fertility will increase yield dramatically. Examples include cultivation practices that will destroy the seeds of various weeds, encourage healthy plant growth and conserve soil moisture. These techniques may consist of mulching, residue management, no-till or zero tillage, reduced field traffic, organic matter addition, suitable fertilization rates based on proper soil assessments, and so on.

Another approach is to integrate a maize crop with crops suitable for crop rotation, mixed cropping or sequential cropping. These crops should be carefully selected based on their effect on weed, pest and disease control and soil fertility. Some management issues to consider are:

(a) Selection of hybrids/varieties best suited to climate conditions and management practices;

(b) Suitable crop rotation and intercropping strategies to improve soil health and reduce pest and disease pressure;

(c) Appropriate use of crop protection measures such as pesticides, herbicides and fungicides, taking into account environmental and health impacts;

(d) Efficient irrigation methods to ensure adequate water supply and avoid waterlogging;

(e) Use of cover crops to improve soil structure and reduce soil erosion;

(f) Soil testing and management to optimize nutrient availability.

### Table 10.3.3: Growth stages of the maize crop

<table>
<thead>
<tr>
<th>Stage</th>
<th>DAS&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>VE</td>
<td>5</td>
<td>The coleoptile emerges from the soil surface.</td>
</tr>
<tr>
<td>V1</td>
<td>9</td>
<td>The collar of the first leaf is visible.</td>
</tr>
<tr>
<td>V2</td>
<td>12</td>
<td>The collar of the second leaf is visible. The collar of leaf number “n” is visible. The maximum value of “n” represents the final number of leaves, which is usually 16–23, but by flowering, the lower 4–7 leaves have disappeared.</td>
</tr>
<tr>
<td>Vn</td>
<td></td>
<td>The collar of leaf number “n” is visible.</td>
</tr>
<tr>
<td>VT</td>
<td>55</td>
<td>The last branch of the tassel is completely visible.</td>
</tr>
<tr>
<td>R0</td>
<td>57</td>
<td>Anthesis or male flowering. Pollen shed begins.</td>
</tr>
<tr>
<td>R1</td>
<td>59</td>
<td>Silks are visible.</td>
</tr>
<tr>
<td>R2</td>
<td>71</td>
<td>Blister stage. Kernels are filled with clear fluid and the embryo can be seen.</td>
</tr>
<tr>
<td>R3</td>
<td>80</td>
<td>Milk stage. Kernels are filled with a white, milky fluid.</td>
</tr>
<tr>
<td>R4</td>
<td>90</td>
<td>Dough stage. Kernels are filled with a white paste. The embryo is about half as wide as the kernel. The top parts of the kernels are filled with solid starch.</td>
</tr>
<tr>
<td>R5</td>
<td>102</td>
<td>Dent stage. If the genotype is a dent type, the grains are dented. The “milk line” is close to the base when the kernel is viewed from the side in both flint and dent types.</td>
</tr>
<tr>
<td>R6</td>
<td>112</td>
<td>Physiological maturity. The black layer is visible at the base of the grain. Grain moisture is usually about 35%.</td>
</tr>
</tbody>
</table>

<sup>a</sup> DAS: days after sowing
(b) Planting at the time most suitable to the farming area and at the correct seeding rates;
(c) Use of agronomic practices suitable to the soil type;
(d) Fertilization according to soil assessments for the desired production levels;
(e) Use of cultural practices most suitable for the control of weeds, diseases and insects;
(f) Following the recommendations provided by agronomic and agrometeorology extension specialists.

Transfer of improved technology may take place through demonstrations of improved crop production technology, Integrated Pest Management training programmes, seed production programmes, and provision of fungicides, herbicides, insecticides and other inputs. The maize technology transfer in the Ghana Grain Development Project was based on three types of activities (Morris et al., 1999): building linkages between research and extension, providing support to extension activities and strengthening seed production activity.

Available varieties are continually changing as new ones are being developed, so there is a need to have up-to-date varietal information. The choice of variety depends on market requirements, environmental conditions, socio-economic considerations, whether the crop is irrigated and the levels of disease and pest resistance required. For example, the state of Queensland, Australia, gives recommendations on factors to be considered as a guide to the selection of maize variety (Hughes, 2006). Time to flowering, cob height, husk cover, disease resistance, “standability”, end use and isolation are mentioned. Hybrid selection should be understood by all and must also have socio-economic components. It is necessary to develop suitable characterization methods for all hybrids that will make the selection process much easier and convenient.

Management information requirements should include communication networks, which should be targeted at:
(a) Information-sharing and communication on hybrid and varietal performance, with expert support;
(b) Training for farmers on such matters as seed selection, management practices and agrometeorological services;
(c) Assessing the performance of varieties in a systematic manner;
(d) Agronomic, pest and soil fertility advisories for farm districts;
(e) Information on newly developed hybrids for farmers;
(f) The response of each hybrid or variety to any of the growth/yield limiting factors;
(g) Information and training on the occurrence of diseases, insects and weeds, including the transboundary spread of diseases;
(h) Disease cycle and climatology (for example, the occurrence of humid conditions);
(i) Symptoms of infestation and crop damage.

For management purposes, the reporting of pests and diseases should include the name of the disease/pest (Latin and/or common), with a description of:
(a) Crop damage;
(b) Symptoms of infections and infestations;
(c) Weather and microclimate conditions for their survival and multiplication;
(d) Life cycle;
(e) Dispersal/spread mechanisms;
(f) Management procedures/ regimes.

10.3.6 User requirements for climate information

The information has to be presented in a language and format that the user understands and it has to be issued at the appropriate time. For example, studies on the use of climate information for production planning examined rainfall dependability, using the coefficient of variation, at some selected centres in Ghana. This showed the months of the year when rainfall can be dependable (Ofori et al., 2004).

10.3.6.1 Information to cope with climatic risk for maize production

According to a study reported by Unganai (2000), any long-range forecast that will potentially benefit farmers has to contain the following information:
(a) Onset date of the rainy season;
(b) Ending date of the rainy season;
(c) Quality of the cropping season rainfall, indicated by the rainfall amount using rainfall percentile studies. Rainfall percentile studies allow for good comparison of rainfall among farming centres or within agroecological zones as well. This also aids in production planning and in the delivery of advisory services;
(d) Temporal and spatial distribution of important climate factors;
(e) Probability, frequency and timing of adverse weather events (such as dry spells or mid-season drought, floods, windstorms, frost) within the season. This will include climatic risk zoning to determine adaptation or avoidance mechanisms during the season;
(f) The patterns of rainfall, temperature, evapotranspiration, relative humidity, sunshine
hours, vapour pressure deficit and other agriculturally significant climate variables. This will include deviations, anomalies and timing of favourable climatic conditions;

(g) Characterization of ecological zones suitable for climate manipulation and maize production purposes using the appropriate climate-based crop yield or growth models;

(h) Interpretation of the above information in terms of which varieties to plant and when to plant.

Such agrometeorological services may be complemented by comparisons with long-term averages and recent seasons and with additional information that was recently shown to be appreciated by farmers and extension agents as described below.

Dry spells that substantially reduce the soil water reservoirs and affect crop yield cause problems for agriculture and other human water needs. Climatic-risk zoning must be used to determine the best planting time to avoid or reduce drought effects on crop development. The following determinations and assessments are thus suggested for coping with climatic risk:

(a) Potential suitability of a specific variety for a given region;

(b) Probability of drought and frost;

(c) Phenological stage most susceptible to drought and frost;

(d) Availability of meteorological data;

(e) Zoning of production districts based on climatic and edaphic conditions;

(f) A water requirement index for each phenological stage.

In addition to the above, water requirement and dryness indices, stored soil moisture and the risk of severe drought must be determined. For example:

$$\text{ETR} = \text{actual crop evapotranspiration}$$
$$\text{ETM} = \text{maximum crop evapotranspiration}$$

$$\text{Dry index, DI} = \left(1 - \frac{\text{ETR}}{\text{ETP}}\right)$$

Suitable drought monitoring and characterization indices therefore are:

(a) Water requirement index;

(b) Drought index;

(c) Available stored water;

(d) Probability of dry spell;

(e) Rainfall anomaly;

(f) Soil moisture-holding characteristics;

(h) Maize fertilization – a methodology for maize fertilization needs to be developed that will have implications for drought/dry spell management or soil moisture storage and nutrient leaching, especially in humid regions.

User requirements for pest and disease management in a climate context are:

(a) Pest and disease identification services;

(b) Life cycle and mode of attack/infestation, simplified in chart form;

(c) Pest and disease mapping for each locality showing the times of the year when climatic conditions favour their survival and multiplication;

(d) Monitoring methods to determine pest and disease presence (visual identification methods must be disseminated);

(e) Assessment of the effectiveness of control measures. This involves:

(i) Assessment of why the method worked or did not work;

(ii) Close consultation with pest advisers or extension officers;

(iii) “What if” analysis (“what if I lose?”, “what if I gain?”);

(iv) Reporting of resistance tolerance;

(v) Determination of environmental influences (rain, humidity, wind, soil, temperature);

(f) Timing of the application of control methods to optimize their effectiveness;

(g) Research on and documentation of social and economic costs of weeds.

User requirements for weed control in a climate context are:

(a) Weed characteristics, including:

(i) Rapid vegetative regeneration;

(ii) Persistence in the soil for long periods;

(iii) Adaptation to varying environments;

(b) Impacts of weeds in terms of:

(i) Crop yield reduction as a result of weeds competing for light, water and nutrients;

(ii) Danger to human beings and/or livestock through poisoning;

(iii) Harbouring of crop pests and diseases;

(iv) Increases in the cost of harvesting.

User requirements for soil and water conservation in a climate context deal with promoting cropping and farming practices, such as manuring and crop residue management, which increase the organic matter content of the soil. For both rainfed and irrigated maize production, the information should contain data on:

(a) Seasonal variations in atmospheric water demand;

(b) Maize crop water use throughout its life cycle and for all varieties;
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(c) Irrigation scheduling techniques;
(d) Soil moisture monitoring techniques;
(e) Measuring or calculating evapotranspiration using on-site evaporation pan or meteorological information;
(f) Monitoring crop conditions;
(g) Training in the “hand feel” method (dig–look–judge–respond) (Moore, 2005).

Other management considerations should include:
(a) Knowledge of hardpans and of soil moisture-holding characteristics;
(b) Knowledge of the crop rooting depths and characteristics, resistance level of hybrids and varieties to drought, disease, frost, and so on;
(c) Water supply: if agriculture is rainfed, the sufficiency and dependability of rainfall during the season needs to be assessed and the months with higher dependability identified. If irrigation is used, then the reliability of the water source needs to be assessed.

User requirements regarding timing of farm operations should consider:
(a) Timing and application of nutrients, especially in humid areas;
(b) Weed control;
(c) Effects of pollination timing on kernel and silk receptivity.

Tactical application of nitrogen after high rainfall at seeding and flag emergence, and application of phosphorus and potassium at seeding, increased crop yields by 79 per cent and 100 per cent at two locations, Boscabel and Orchid Valley, according to Hill et al. (2005). Similar treatment could be done to maize crops at specific locations.

User requirements for the resistance/tolerance level of hybrids include the assessment of resistance or tolerance of all hybrids to weed, pest, disease and drought levels under different environments and edaphic conditions for their overall potential. This will aid in varietal selection for a particular environment. In some cases, resistance or tolerance levels are quantified and acceptable levels developed. Factors to look at are:
(a) Virus resistance level;
(b) Insect or pest resistance level;
(c) Fungal resistance level;
(d) Bacterial resistance level;
(e) Herbicide resistance level;
(f) Drought or frost resistance level;
(g) Weed infestation resistance;
(h) Nitrogen use efficiency;
(i) Response to nitrogen fertilization.

These levels should be quantified as an aid to farmers and other stakeholders in making decisions on which variety to use. The potential for breeding maize with greater nitrogen use efficiency, characterization of the nitrogen response to local and improved maize varieties, and identification of secondary traits associated with tolerance to low nitrogen stress may be required.

User requirements for agrometeorological information on the crop may be listed as follows:
(a) Maturation periods in days or degree-days/heat units for all maize hybrids/varieties;
(b) Climatic risk zoning to determine the best planting time to avoid or reduce the risk of encountering drought during crop development;
(c) Matching crop water requirements with the season;
(d) Information about the weather factors that are conducive to infestation by insects and pathogens to allow timeliness of control practices;
(e) Drought/frost stress characteristics of the crop;
(f) Growth stage characterization;
(g) Strengthening farmer appreciation of crop growth/crop yield models;
(h) Development of accurate models to estimate crop performance.

10.3.7 Examples of agrometeorological services related to this crop

Three case studies of on-station design trials of agroforestry systems with maize, provided as agrometeorological services to farmers in Africa, were identified in the literature. The first example was an alley cropping design on flat land in the semi-arid Machakos district of Kenya (Mungai et al., 1996). In the alley cropping system studied, every fourth row of maize was replaced by a row of *Cassia siamea* trees and loppings were incorporated into the soil at the beginning of each maize-growing season. In this kind of replacement agroforestry, it was found that the difference between yields in agroforestry systems and yields in systems that use monocropping controls is larger at higher rainfall levels and with better rainfall distributions.

This design on flat land proved that it was difficult to increase crop yields considerably by alley cropping in the semi-arid tropics in years other than those with appreciably above-average rainfall and with a beneficial rainfall distribution. There is even a relatively low rainfall level below which the controls often do better. Since the late 1980s and early 1990s, it has been clear that adoption of such
systems by farmers has been much lower than expected. This early work highlighted why farmers have such a negative view of alley cropping. Low biomass production that insufficiently improves soil conditions through mulching, and high competition for resources between trees and crops, are the main causes. Farmers are thus advised not to apply such systems on flat land in semi-arid conditions. That was the agrometeorological service delivered by this research in the late 1980s and disseminated in the early 1990s through extension channels of the (then) International Council for Research in Agroforestry (ICRAF) (Mungai et al., 2001).

In the second case study, *Senna siamea* contour hedgerows with inter-row distances of 4 m were used “on-station” for erosion control on a 14 per cent slope of an Alfisol at the ICRAF research station in the semi-arid district of Machakos, Kenya. For one of the two rainy seasons of each year, the hedgerows were intercropped with maize, without the use of fertilizers. There were four rows of maize in the alleys formed by the hedgerows. Cumulative results for four seasons showed that the most successful treatment for soil loss and runoff reduction was the combination of hedges and surface spreading of their prunings as mulch, done just before the start of the rainy seasons. This reduced cumulative runoff from close to 100 mm to only 20 mm and cumulative soil loss from more than 100 t/ha to only 2 t/ha (Stigter et al., 2005a). This was at the expense of 35 per cent of the maize yields.

These significant yield reductions were due to an increase in competition from hedges that were now more mature, compared to the competition from the younger hedges in earlier experiments. The planting of hedgerows alone, without applying the mulch, was appreciably less effective in both soil loss and runoff reduction and came at the expense of even more maize yield. Mulch appeared to be the main factor reducing soil evaporation, but under high soil evaporation of between 50 per cent and (an upper limit of) 65 per cent of the rainfall, evaporation reduction did not exceed the range of a relative 5 per cent and 10 per cent. This was due to the low biomass production in semi-arid conditions (Kinama et al., 2005). Experiments with *Panicum maximum* grass strips (and no mulch) instead of the low trees gave results for runoff and soil loss reduction that were halfway between the values for the hedges with and without mulch application, but the yield reductions recorded were the largest among all the treatments.

In highlighting the consequences of the system design for farmers, provided as an agrometeorological service, it should be kept in mind that alley farming on sloping land was earlier shown to be successful only if the system was adapted to the particular needs of the farmers concerned. The grass strips were more effective in preventing soil erosion than the hedgerows because of the compactness and thickness of the grass strips. They are more effective in reducing runoff speed and trapping soil than the thinner and appreciably less dense hedgerows. For lower-input farmers, grass strips and highly competitive trees with high biomass density close to the ground, even when less efficient in direct erosion control, may deliver highly needed thatching material and/or fodder and save money for durable erosion-control embankment stabilisation (Stigter et al., 2005a).

In the third case study, in the semi-arid Laikipia District, Kenya, *Coleus barbatus* hedges solved existing wind problems where previously the wind had blown off maize stalk mulches and was mechanically shaking the maize. Protection was assisted by *Grevillea robusta* (silky oak) trees as used in the demonstration agroforestry plots with maize and beans (Oteng’i et al., 2000). In the demonstration plots, the hedge roots were pruned, as were half of the trees. The positive moisture effects were stronger closer to the pruned trees.

The agroforestry intervention with pruned older trees and maize stalks used for mulching did not negatively influence maize yields in the wettest season and showed a positive effect on maize biomass yields in the driest season. Comparison of yield differences in mulched and pruned plots in the wettest season indicated that, for maize, tree pruning was more effective than mulching under these conditions. A combination of the water conservation measures of root pruning, mulching and minimum tillage was to be preferred for the maize/beans intercrop in this agroforestry system for seasons with very low rainfall. More overlapping of depletion zones of the three root systems would have influenced the pruned plot yields of the intercrop more seriously (Stigter et al., 2005b).

The results showed that under the very difficult semi-arid conditions in Laikipia, the mulched tree-cum-hedge pruned agroforestry system helped to limit land degradation overall. The farming conditions are extremely marginal, however, and economically more viable systems must be developed as (agrometeorological) services to help the farmers concerned (Stigter et al., 2005b).
10.4 AGROMETEOROLOGY AND PEARL MILLET PRODUCTION

10.4.1 Importance of pearl millet in various climates

Pearl millet is a cereal crop that is widely grown under rainfed conditions in the arid and semi-arid regions of Africa and southern Asia. It is grown under intensive cultivation as a forage crop on other continents. Pearl millet is suited to 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. In addition to millet’s use as food for human consumption, its 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, and so on (IFAD, 1999).

Pearl millet (Pennisetum glaucum (L) R. Br.) is one of the four most important cereals grown in the tropics (the others are rice, maize and sorghum) (Syngenta Foundation for Sustainable Agriculture, 2005). It is believed to have descended from a West African wild grass that 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. The area planted annually with pearl millet is estimated at 15 million hectares in Africa and 14 million hectares in Asia. Global production exceeds 10 million tonnes per year (National Research Council, 1996). The food value of pearl millet is high. Trials in India have shown that pearl millet is nutritionally superior for human growth when compared to maize and rice. The protein content of pearl millet is higher than maize and it also 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 favourably 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 most important crop in sub-Saharan Africa, and the main producing countries are Burkina Faso, Chad, Niger, Nigeria, Mali, Mauritania and Senegal in the west, and 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 Gujarat, Haryana, Rajasthan, Maharashtra and Uttar Pradesh (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 per cent of the area is in Punjab, and 37.8 per cent is in Sindh. Ninety per cent 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 Australia, Canada, China, Mexico, the Russian Federation and the United States. In most of these other countries, pearl millet is grown primarily as a forage crop for livestock production (National Research Foundation, 1996; Syngenta Foundation for Sustainable Agriculture, 2005).

10.4.2 The influences of agroclimatological variables on pearl millet

The climate of most areas where pearl millet is produced 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, day length (photoperiod), radiation, and wind. The impact of these variables is dependent upon the developmental stage of the crop.

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

(a) GS1: Growth stage one, or sowing to panicle differentiation;
10.4.2.1 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 more definite (Kowal and Kassam, 1978). Some of the agro climatic features of rainfall distribution include:

(a) Total rainfall during a season;
(b) The onset of the rainy season;
(c) The termination of the rainy season;
(d) The distribution of rainfall during the rainy season, particularly early in the growth cycle.

At sowing, poor soil moisture 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 resow when rains recur. 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.

During GS2, or the vegetative growth period, the crop is well adapted to water deficits (Mahalakshmi et al., 1988) and can tolerate intermittent breaks in rainfall, which are a common feature of the climate of millet-producing areas.

During GS2, or the vegetative growth period, the crop is most sensitive 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.

10.4.2.2 Temperature

A large number of 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, 1983b; Gregory, 1983; Khalifa and Ong, 1990). Pearl millet development begins at a base temperature around 12°C, with an optimum temperature between 30°C and 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 a high radiation load and scarce rainfall. In some parts of India, however, soil temperatures can be a concern. Soil temperatures influence all aspects of early vegetative development; the emergence of seedlings; and the initiation, appearance and final number of leaves and tillers (Ong, 1993a).

With regard to the germination and emergence stage (GS1), soil temperatures must reach 12°C for germination to begin, as noted earlier. 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, sand blasting and the burying of young seedlings under the sand further complicate the problem.

At the development stage (GS2), the temperature requirements of pearl millet depend on the cultivar. Diop (1999) found an optimum range of 22°C to 35°C for plant growth and a maximum of 40°C to 45°C. The optimum temperature for root elongation is 32°C. A WMO report on the agrometeorology of millet (WMO, 1993) states that pearl millet requires temperatures between 22°C and 36°C for a good photosynthetic response, with an optimum range of 31°C to 35°C.

Cantini (1995) reports that leaf appearance and expansion rates are positively correlated with temperature, and that 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 primordia on the main stem apex does not change from 18°C 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 explain why the number of grains produced is inversely related to temperature from 22°C to 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 LAI increases.

As for the reproductive stage (GS3), both the rate of spikelet production and the duration of the early reproductive phase are very sensitive to soil temperatures since the meristem is at or close to the soil surface. Grain setting is optimum from 22°C to 25°C and declines at temperatures below and above this range, while grain mass steadily declines 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) results 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 is due to sterility of florets and pollen grains induced by lower temperatures (Fussell et al., 1980; Mashingaidze and Muchena, 1982).

10.4.2.3 Day length/photoperiod

Day length, 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 (Syngenta Foundation for Sustainable Agriculture, 2005).

The two major millet-growing zones of the world lie in different latitudes, from 11° N to 14° N in western and central Africa and between 25° N and 30° N in north-western India. In both these zones, the length of the growing season varies from 10 to 18 weeks (Kowal and Kassam, 1978; Virmani et al., 1982). The length of the growing season is inversely related to the latitude and this relationship is more pronounced in West Africa, where season length changes markedly over a relatively small distance 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 favourable (Mahalakshmi and Bidinger, 1985). This helps minimize grain mould and 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 (WMO, 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 day length 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, although there is a minimum value that represents the “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) indicate, 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.

10.4.2.4 Solar radiation

Solar radiation is an important asset in crop production. The amount of incoming radiation sets the limits for the production of dry matter. Radiation has two roles in crop production. A segment of total radiation is called photosynthetically active radiation (PAR), which is required for photosynthesis. The solar radiation that heats the Earth's surface provides the thermal conditions necessary for physiological processes (WMO, 1996). Fortunately, radiation is seldom a limiting factor in the tropics.

Pearl millet is a C₄-type plant, which means that it has a high photosynthetic efficiency, particularly under high temperature conditions, because of reduced photorespiration (WMO, 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 both in the morphogenetic processes of growth and in determining the flowering of pearl millet. Within the plant cover, the redistribution of solar radiation involves leaf area density, plant architecture, leaf angle and
planting density (Bégué, 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 (WMO, 1993). The following equation illustrates this relationship:

\[
\text{Total biomass (g m}^{-2}\text{)} = \text{PAR}_a \times E_c \times t \quad (10.4)
\]

where \(\text{PAR}_a\) is absorbed photosynthetically active radiation, \(E_c\) is conversion efficiency of PAR into biomass (g MJ\(^{-1}\)) and \(t\) is time.

The conversion efficiency of PAR (\(E_c\)), also called \(E_b\) (Birch, 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, \(E_{\text{wa}}\) is not affected by day length or crop density. Even when temperature, when its values are above 21.5°C, does not affect \(E_{\text{wa}}\) despite its effect on the growth cycle. High atmospheric water saturation deficit and/or lack of soil moisture, however, can lower the radiation conversion efficiency because of stomatal closure triggered by these environmental conditions (WMO, 1993).

Several studies have been conducted to determine the radiation use efficiency of pearl millet (McIntyre et al., 1993; Bégué et al., 1991). Radiation use efficiency (RUE) is defined as the dry matter production per unit of incoming solar energy. In a study in Niger (Bégué et al., 1991), measurements of the components of radiative transfer were combined with measurements of biomass and LAI. A linear relationship was found between PAR and 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). When irrigated and non-irrigated responses to extreme temperatures and moisture stress were compared, RUE did not change under varying temperature regimes when irrigation was applied. The radiation use efficiency of the non-irrigated plots did decline under extremely high temperatures, however.

10.4.2.5 Wind

In West Africa, heavy winds associated with thunderstorms are common during the crop season. These winds are laden with dust particles that reduce visibility and the incoming amount and quality of radiation; these particles form deposits on leaf surfaces that may affect photosynthesis (WMO, 1996). On the sandy soils in the southern Sahel, wind erosion owing to frequent sandstorms, especially at the beginning of the rainy season, is one of the constraints to crop growth (Michels et al., 1993). If sufficiently buried, these “pockets” of plants must be replanted. Surviving plants from partially covered pockets show delays in growth and development. The maximum plant height and leaf number are lower, with a significant reduction in the leaf area index. Grain yield from unaffected pockets is nearly twice that of pockets that are partially covered.

In shelterbelt studies in northern Nigeria, it was shown that *Eucalyptus camaldulensis* shelterbelts positively influenced yields of millet crops 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 per cent less when both methods of determining the onset of the growing season were used. Soil moisture availability early in the season was the largest determinant in yield differences among plots, as a result of its influence on growth, tillering and grain filling. Substantial yield differences as a function of the distance from the belts could be explained by soil moisture at sowing and the effects on crop growth conditions resulting from hot, dry turbulent air generated by the belts. The shelterbelts settled drifting sand and undulations and encouraged the return of soil-protecting grasses (Onyewotu et al., 2003). A number of the factors that should be taken into consideration in the design and development of shelterbelts are described by Stigter (2005).

10.4.3 Management aspects of pearl millet in various environments

Traditional cropping systems in the Sahel consist essentially of continuous pearl millet/cowpea intercropping with low plant populations and no chemical fertilizers. All production operations are done manually in these traditional systems (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. Because prolonged droughts can occur after sowing and during early the early seedling stages, however, 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 development. Drought conditions combined with high temperatures can be highly detrimental to the emergence and development of the young seedlings.
Strong winds can also cause damage to the young seedlings and cover them with sand.

In terms of land preparation and cultivation, in most cases little or no tillage is done and weeding is started right after emergence in Africa. In sandy soils, the ground is dug over with a hoe and weeded prior to planting. Warm soils are required since higher temperatures encourage rapid germination (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 seed-bed. Land preparation is usually inadequate, however, 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 needed 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.

A major problem of rainfed 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 relationships as criteria. This was taken as the first 10-day period in the season when the amount of rainfall is equal to or greater than 25 mm, but with a subsequent 10-day period in which the amount of rainfall is at least equal to half the evapotranspiration 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 of Ramadan, provided that it has been at least seven 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 due mainly to soil water availability, particularly during the seedling stage.

In Pakistan, millet fields in the rainfed barani areas are 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).

The most common soil fertility management practice with pearl millet is fallowing. Sometimes, manuring is practiced either through corolling (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 and 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, United States, to evaluate different summer forages, pearl millet was as productive as the average sorghum sudan but required one fifth the nitrogen (N) and was more efficient with the N it received (Johnson, 2006). Increased fertility also results in an increase in water use efficiency. In a four-year study at the International Crops Research Institute for the Semi-Arid Tropics (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 per cent.
CHAPTER 10. AGROMETEOROLOGY OF SOME SELECTED CROPS

With regard to moisture conservation, evaporation from the soil surface constitutes a large proportion of evapotranspiration (ET) 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 fed 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 evapotranspiration (Bmerican, 2010). 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 Visser, 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 so 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 colour 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 dessicated. 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 a significant reduction in moisture loss. Because of limited labour resources, however, it would be unrealistic to expect subsidence farmers to till entire fields with the hand-operated hilaire after each rain event. In order to render this technique useful to farmers, an 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 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 5 000 to 20 000 “hills” ha⁻¹ increased yield and ET efficiency significantly despite low fertility, even during 1984, the driest year on record. There appears to be no justification, at least in terms of crop water use, for wide spacing. Canopy cover can also be increased by the introduction of an intercrop. In semi-arid West Africa, pearl millet is most often intercropped with cowpea. Intercropping with cowpea has been reported to increase pearl millet grain yield by between 15 and 103 per cent in Mali.

Although pearl millet in India is the crop of the rural poor in the country’s harshest agricultural environments, 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 pays for the cost of the seed and other risks associated with hybrid cultivation (WISARD, 1999). 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 per cent, and are estimated to average 14 per cent across 10 million ha in India.

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 despite low fertility, even in widely spaced rows. This is perceived to be a practice that reduces pearl millet crop failure. As a result, the 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 5 000 to 20 000 “hills” ha⁻¹ increased yield and ET efficiency significantly despite low fertility, even during 1984, the driest year on record. There appears to be no justification, at least in terms of crop water use, for wide spacing. Canopy cover can also be increased by the introduction of an intercrop. In semi-arid West Africa, pearl millet is most often intercropped with cowpea. Intercropping with cowpea has been reported to increase pearl millet grain yield by between 15 and 103 per cent in Mali.

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10.4.4 Other background information on pearl millet

10.4.4.1 Drought tolerance mechanisms

Deep root penetration is an important aspect of the ability of pearl millet to survive under high stress. Pearl millet roots can penetrate up to 180 cm deep, with approximately two thirds of the root system in the top 45 per cent 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 are maintained through periods of severe drought (Zegada-Lizarazu, 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 at the basal nodes of the stem 6 to 7 days after seedling emergence. These grow rapidly and form a root system of secondary and tertiary roots that are the principal 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.

In terms of leaf structure, stomata are present on both leaf surfaces. The colour of the leaves varies from light green to yellow to deep purple. The maximum leaf area (LAI) occurs at the time of 50 per cent flowering, when the majority of the tillers have produced leaves. After flowering there is a decline in leaf area, and during this 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 by 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). Leaves will begin to senesce, however, thus reducing the LAI of the plant canopy. Stomatal regulation and leaf senescence are not mutually exclusive; stomatal conductance decreases as leaf area increases. Conversely, a reduction in transpiring area increases stomatal conductance in the remaining leaves.

10.4.4.2 Diseases, pests and weeds

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

Downy mildew (*Sclerospora graminicola* (Sacc.)) constitutes the major disease risk to the successful cultivation of pearl millet (WISARD, 1999), particularly in India. Up to 30 per cent of the harvest in India can be lost during years of severe attack, with losses in individual fields reaching nearly 100 per cent (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 soil-borne sexual spores or oospores that can survive in soils for several years are the primary source of inoculum for downy mildew disease. Their thick cell walls protect them from desiccation and serve as an impermeable membrane. During cool and humid nights, the systemically infected leaves produce abundant sporangia on the abaxial surface. The hot and dry environmental conditions favourable for pearl millet growth may not be conducive for sporangial production and survival, however (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, its severity, and the yield losses of two pearl millet varieties (local and improved) due to the disease were determined in field studies (Zarafi 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 were 40.88 and 45.39 per cent in a local variety and 43.00 and 18.60 percent in an improved variety in the 2000 and 2001 cropping seasons, respectively.

In a three-year study in Nigeria, Zarafi (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* 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 tonnes (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 favour *Striga* infestations. *Striga* can be partially controlled by pre-treatment of seeds with herbicides that reduce or prevent 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 this resistance can be transferred to varieties acceptable to farmers (Syngenta Foundation for Sustainable Agriculture, 2006).

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, 1988). Moderate temperatures (25°C–30°C) rather than cool temperatures, high relative humidity (>80 per cent) and long days seem to favour disease development (Kousik et al., 1988; Thakur, 1990). 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 in digestible dry matter yield of forage. Animal production could be improved by identifying rust resistance among popular and potential cultivars. In studies conducted in 1997 and 1998, several resistant varieties were identified. Of all the environmental parameters evaluated, only average temperatures below 27°C were consistently associated with the onset of rust epidemics (Panwar and Wilson, 2001).

10.4.4.3 **Insects and pests**

Pearl millet has relatively few menacing insect pest problems. In the Asian subcontinent, white grubs are the major pests (Rachie and Majumdar, 1980). In West Africa, there is a range of insect pests that damage the crop, resulting in economic losses; the major ones are the earhead caterpillar (*Raghuva*), stem borer (*Acigona*), midge (*Geromyia pennisetii*) and several species of grasshoppers.

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 a 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 a preventive measure against white grub must be applied at the time of sowing.

Pest surveys in West Africa indicate that crops are devastated by infestations of earhead caterpillars (*Raghuva*). The number of surviving diapausing pupae emerging from the soil is associated with soil temperature and moisture at different depths from November to May. In addition, there is a close relationship between moth emergence and the onset of rain and soil moisture, which are key factors in diapause termination. The increase in soil moisture content and lower soil temperatures in the upper
The time of the onset of rainfall and the total amount of rainfall during the crop season is related to the stem borer (*Acigona ignefusalis*) population (Nwanze, 1989). There is a need for knowledge of diapausing populations and the relationship between insect pests and rainfall during the season in regions where sporadic outbreaks occur in order to integrate the weather parameters with the population dynamics of the pests.

10.4.5. **User requirements for agrometeorological information**

As indicated in other sections, to be of use the agrometeorological information provided must meet several important criteria. The information must be timely and accurate, it must address specific needs, and it must be in a form that can be easily and accurately interpreted by the producer, extension service or whoever provides advice to the producers. User requirements will vary greatly with the area where pearl millet is being grown. The major areas producing pearl millet are located in the semi-arid tropics of Africa and India. As stated, a majority of those producers are subsistence farmers with very limited resources. The farms are small and usually cultivated by hand. But other millet-producing areas in mid-latitude areas involve more intensive production practices and are highly mechanized. The requirements for agrometeorological information can be separated into the current growing season, overall seasonal differences and longer-term features of the climate.

In terms of information for the current growing season, given limited means, both from a climate perspective and owing to economic constraints, it is extremely important to minimize risk and maximize the use of whatever resources are 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 of vital importance. 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 labour and land allocations, obtain different varieties and prepare fields in different locations.

In order of declining priority, the most salient rainfall parameters farmers want in a forecast are: timing of the onset and end of the rainy season; likelihood of water deficits, that is, the likely distribution pattern over the growing season; and the total amount of rainfall. In the Sahel, information on seasonal rainfall quantities can help farmers 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. They must also be delivered in the most appropriate form and language, by credible sources. This task becomes even more challenging because farmers have different levels of access to formal education, the availability of extension-type services varies, and there are differences in adherence to local religious beliefs. This affects the extent to which local knowledge, including local climate forecasts, remains a viable basis for farmer decisions.

Agrometeorological information required to cope with climatic risks for any given season would include:

(a) The current climate regime and its effect on the onset of the rainy season, including the expected date of the onset of rain. This could also aid in the medium-term planting outlook. Information on regional climate dynamics might help improve crop production locally. It has been shown that the regional onset of the monsoon is very close to the ideal sowing date (Sultan et al., 2005);

(b) The development/adaptation of more scientific approaches to determine when sowing should begin;

(c) Timely information on the onset of the rainy season. Weather forecasts should include information on both temperatures and the likelihood of future precipitation;

(d) Expected conditions immediately after the onset of rain. Wind and high temperatures are a common problem immediately following planting and seedling emergence;

(e) Date of the end of the rainy season;
(f) Development/adaptation of models for forecasting the development of critical disease and insect outbreaks;
(g) Development of simple, practical methods of getting the appropriate information to farmers to help them maximize their limited resources.

With regard to long-term planning, research suggests reduced African food production if the global climate changes towards more El Niño-like conditions, as most climate models predict. Management measures include annual changes in crop selection and storage strategies in response to predictions calling for El Niño–Southern Oscillation and North Atlantic Oscillation conditions for the next growing season. Long-term planning can also be important in the development of agricultural policy by regional and national governments and international organizations. The development of longer-term policies must stem from 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 found 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 determining the suitability of a locality for millet production.

The derived rainfall parameters, such as the onset of rains, cessation of rains, duration of the rainy season, sowing rains and rainfall probabilities for specific phenological phases (sowing time, flowering, harvesting, and so forth), are very useful for long-term agricultural planning. Rainfall probabilities can be estimated using the gamma distribution since it fits better than other mathematical distributions for rainfall data (WMO, 1996).

Information required to cope with climatic risks for longer-term planning would include:
(a) The probability, frequency and timing of adverse weather conditions, including the distribution of rainfall, windstorms and beginning and end of the rainy season;
(b) The pattern of rainfall, temperature, evapotranspiration, relative humidity, sunshine hours, vapour pressure deficits and other agriculturally significant climate variables;
(c) Agroclimatological analyses of these significant variables for evaluating additional production areas, particularly in the light of concern about potential changing climates. Climatic risk zoning may be used to determine the best planting zoning to avoid or reduce drought effects on crop development. The following determinations/assessments are thus suggested for coping with climatic risk:
(a) Potential suitability of a specific variety for a given region;
(b) Probability of drought at critical points in the growing season;
(c) Phenological stage most susceptible to drought;
(d) Availability of local meteorological data;
(e) Zoning of production districts based on climatic and edaphic conditions;
(f) Information about the weather factors that are conducive to infestation by insects and infestation by pathogens to allow timeliness of control practices;
(g) Suitable drought monitoring and characterization indices, such as:
(i) Water requirement index;
(ii) Drought index;
(iii) Available stored water;
(iv) Probability of dry spells;
(v) Rainfall anomaly;
(vi) Soil moisture-holding characteristics.

10.4.6. Agrometeorological services related to pearl millet in Africa and India

10.4.6.1 Africa: Example 1

The information presented in this example has been drawn from Oluwasemire et al. (2002) and Stigter et al. (2005). The major cereals that are 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 minimize risks and exploit resources in a good cropping season. Experiments to determine what sort of improved answers local intercropping systems could give to land degradation were conducted during the 1994 and 1995 rainy seasons. The experiences highlighted the usefulness and desirability of an agrometeorological service that would be aimed at improving the cereal/legume systems in the Nigerian arid and semi-arid zones. In parallel, genetically superior crop cultivars and the manipulation of the component densities would be included in the suggested project, along with the improvement of microclimatic variables. An ameliora-
tion of the cereal/legume intercropping systems may involve a reduction in plant density of the tillering millet component, which accumulates dry matter more rapidly, while the density of the low-growing and ground-covering cowpea component is increased. The results showed that abundant organic manure in combination with agrometeorological services on microclimate improvements related to intercrop manipulation may control near-surface land degradation in northern Nigeria under acceptable sustainable yields. Appropriate policy environments, in economics and research, must enhance these efforts.

10.4.6.2 Africa: Example 2

This example is based on Onyewotu et al., (2003, 2004) and Stigter et al. (2005) and it illustrates failures in original attempts to protect millet crops in Sahelian Nigeria from advected heat by multiple shelterbelts. Farmers had to learn for themselves that the crops were sufficiently protected only in close proximity to the belts. Participatory experiments demonstrated as an agrometeorological service why this was the case, only at a much later date. At this same very late stage, while the farmers had long complained about allelopathy of the trees, it was shown that this did not exist and that root pruning and branch pruning did away indeed with all competition for resources between trees and millet. This showed the maximum benefits of the rehabilitation of the degraded land as originally designed. As the soil and crop protection measures were insufficient, the farmers of sheltered land were economically worse off. The research confirmed views that have been held for close to 20 years, namely, 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. 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. The answer of sufficient tree densities to prevent advected heat from spoiling pre-sowing soil water conditions and unprotected millet crop growth was only found as an agrometeorological service in the framework of this research, however.

10.4.6.3 India

The India Meteorological Department recognized the importance of meteorology in increasing food production and established its Division of Agricultural Meteorology (DAM) 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/biweekly Agromet Advisory Bulletins. The 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 ay-to-day farming operations. The advisories take into account the stage of the crops, agricultural operations in progress, the 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 to help them protect their crops from adverse weather and make the best use of prevailing favourable weather to increase production.

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

10.4.6.4 India: Example 1

This example is taken from http://www.indiaweatherwatch.org/agroad/Jodhpur.pdf.

Agrometeorological Advisory Services Central Arid Zone Research Institute (CAZRI), Jodhpur

Date: 16 March 2007

Weather Forecast:

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

Agrometeorological Advisory:

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

– 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.
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 thiram 3 gm per kg seed.

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 monochrotophos 10 ml in 10 litres of water is recommended.

10.5 AGROMETEOROLOGY AND POTATO PRODUCTION

10.5.1 Importance of potato in various climates

The potato (Solanum tuberosum L.) is a member of the nightshade family (Solanaceae) and is a major world food crop and by far the most important vegetable crop in terms of quantities produced and consumed worldwide (FAO, 2005). Potato is exceeded only by wheat (Triticum aestivum L.), rice (Oryza sativa L.) and maize (Zea mays L.) in world production for human consumption (Bowen, 2003). Potato tubers give an exceptionally high yield and find their way into a wide variety of table, processed, livestock feed, and industrial products (Feustel, 1987; Talburt, 1987). Potato provides nutritious food in a diversity of environments. Potato can be an important food for the rising world population and has the potential for increased vitamin C and protein content.

The principal limiting factors for potato production are heat and water stresses. The effects of these factors on physiology, yield and grade of potato crop are thoroughly discussed herein. The meteorological elements governing growth, development, production and quality of potato tubers at a given site are basically air and soil temperatures, solar radiation, photoperiod, soil moisture and crop water use or evapotranspiration.

Potato originated from tropical areas of high altitude in the Andes. The crop is grown throughout the world but is of particular importance in temperate climates. Present world production is 329 106 Mg fresh tubers from 19.1 million ha (FAO, 2005). The major world producers, in order of production, are China, Russian Federation, India, United States, Ukraine, Poland, Germany, Belarus, Netherlands, United Kingdom, Canada, Turkey and Romania (FAO, 2005).

The above-ground stems of potato plants are erect in early stages of development but later become...
spreading and prostrate or semi-prostrate. The tuber is an enlarged underground stem. The tubers have buds or eyes, from which sprouts arise under certain conditions. Tubers are harvested for both food and seed. The flowers and fruits are only important to potato breeders.

Potato has a relatively shallow, fibrous root system with the majority of the roots in the upper 0.3 m of soil (Leszczynski and Tanner, 1976; Tanner et al., 1982). The root system develops rapidly during early growth and achieves maximum development by midseason. Thereafter, root length, density and mass decrease as the plant matures. Rooting depths of 1.2 m or more have been reported for potato under favourable soil conditions (Durrant et al., 1973; Fulton, 1970). Potato extracts less water from the soil than barley (Hordeum vulgare L.) and sugar beet (Beta vulgaris L.) and the differences are more pronounced below 0.6 m depth (Durrant et al., 1973).

The origin of potato in cool climates with equatorial day lengths, as well as the shallow potato root systems, have consequences for the agrometeorological responses of the crop. Knowledge of climatic requirements of potato and its physiological responses to the environment is extremely important to help growers produce high yields with good tuber quality under site-specific atmospheric conditions. Crop weather models can be used to provide estimates of potato yield as a function of climatic factors at a particular locality. The SUBSTOR-Potato model, for instance, takes into consideration daily data of temperature, photoperiod, intercepted solar radiation, soil water and nitrogen supply. The model simulated fresh tuber yields ranging from 4 Mg ha\(^{-1}\) to 56 Mg ha\(^{-1}\) due to differences in climate, soils, cultivars and management practices (Bowen, 2003).

According to the Alberta Agriculture, Food and Rural Development Department (2005), the potato plant has five growth stages: sprout development (I); plant establishment (II); tuber initiation (III); tuber bulking (IV); and tuber maturation (V). Timing and duration of these growth stages depend upon environmental factors, such as elevation and temperature, soil, moisture availability, cultivar and geographic location.

At growth stage I, sprouts develop from eyes on seed tubers and grow upward to emerge from the soil, roots begin to develop at the base of emerging sprouts and the seed piece is the sole energy source for growth during this stage. At stage II, leaves and branches develop on emerged sprouts, roots and stolons develop below ground and photosynthesis begins. Potato development in stages I and II lasts from 30 to 70 days, depending on planting date, physiological age of the seed tubers, cultivar, soil temperature and other environmental factors. At stage III, tubers form at stolon tips but are not yet appreciably enlarged, and in most cultivars the end of this stage coincides with early flowering that lasts roughly two weeks on average. At stage IV, tuber cells expand with the accumulation of water, nutrients and carbohydrates. During the tuber bulking stage, tubers become the dominant site for carbohydrate and inorganic nutrient storage. Tuber bulking can continue up to three months as a function of the cultivar and environmental conditions. During stage V, photosynthesis gradually decreases, leaves turn yellow, tuber growth rate slows and the vines die. Maturation may not occur in the field when a long-season variety like Russet Burbank is grown in a short-season production area.

10.5.2 Agroclimatology of potato (and some management aspects)

Kooman et al. (1996) report three phenomenological phases in the allocation of dry matter that is accumulated daily. Initially, dry matter is divided between stems and leaves (growth stage II). In the second phase, which starts at tuber initiation, an increasing amount of accumulated dry matter is allocated to the tubers and a decreasing fraction to the leaves (growth stages III and IV). In the third phase, all assimilates are allocated to the tubers (growth stage V). Leaf growth stops and photosynthesis eventually stops because of leaf senescence. Climatic factors influence all three phenomenological phases. The duration of the first phase, comprising the development period between emergence and tuber initiation, is shortened by short days and temperatures less than 20°C. Tuber initiation is slower at temperatures over 20°C. The duration of the second phase is affected by temperature, with an optimum between 16°C and 18°C (van Heemst, 1986) or 14°C and 22°C (Ingram and McCloud, 1984), and by solar radiation. Crop senescence is shortened by high temperatures, especially greater than 30°C (Midmore, 1990). The effects of agroclimatological factors on physiological parameters of potato, especially on tuber yield, grade and internal quality, will be discussed below.

10.5.2.1 Air temperature, solar radiation and photoperiod

Owing to the interactive effects of air temperature, photoperiod (day length), solar radiation and cultivar on the tuberization stimulus, these meteorological
variables will be discussed together, with an emphasis on physiological responses to one or another climatic element consistent with the specific objectives of each research project.

The review by Haverkort (1990) points out that potato is best adapted to cool climates such as tropical highlands with mean daily temperatures between 15°C and 18°C, as encountered in its centre of origin. Higher temperatures favour foliar development and retard tuberization. In addition, heat stress leads to a higher number of smaller tubers per plant, to lower tuber specific gravity with reduced dry matter content, and usually to a paler skin colour of the tubers.

De Temmerman et al. (2002) examined the effect of latitude, seasonal mean air temperature (ranging from 13.8°C to 19.9°C), global solar radiation (ranging from 12.0 to 21.3 MJ m⁻² d⁻¹), air humidity, soil moisture and atmospheric CO₂ concentrations on tuber yield in European experiments. Ignoring CO₂ enrichment, the yield of potato (cv. “Bintje”) increased from southern to northern Europe. Marketable tuber yields increased at higher latitudes. The authors ascribed this result to lower temperatures, lower vapour pressure deficits and longer day lengths at higher latitudes, which in turn resulted in longer effective growing seasons.

Climatic conditions, as affected not only by the latitude but also by altitude, influence potato plant growth and development. Moreno (1985) found that plants grown at low (coastal) altitudes have a low yield of tubers per plant as compared with those grown in the Andean highlands. Tubers harvested from coastally grown plants had lower free amid acid and amide contents and a higher content of tuber protein than those from the Andean highland. Coastal tubers also had less total sugar content than Andean tubers.

Haverkort (1990) reports that an inconvenience of the short-day sensitivity of the potato is that cultivars that make use of the whole growing season and produce well in northern Europe (with a growing season of 5 to 6 months), may mature too early and senesce between 60 and 70 days after planting in the equatorial highlands and consequently yield less. Cultivars that perform well at low latitudes in a growing season of between 3 and 4 months start tuberizing late and mature too late at 50°N.

Photoperiodic responses are mediated by endogenous plant hormones. Relatively high gibberellic acid (GA) levels reduce or stop tuber growth and relatively high abscisic acid levels promote tuber growth. In some potato cultivars and species, long photoperiods produce high GA levels that prevent tuber growth. This can be a problem for temperate regions, which have long photoperiods during their usual crop season. Fortunately, many of the North American cultivars are “day neutral” and presumably have lost the GA-photoperiod response (Dwelle, 1985).

Carbon dioxide concentration can also exert a strong influence on potato productivity. The influence of carbon dioxide depends on solar irradiance (Wheeler et al., 1991). Potato cultivars (“Norland”, Russet Burbank and “Denali”) were grown at CO₂ levels of 350 or 1 000 μmol mol⁻¹, irradiance of 400 or 800 μE m⁻² s⁻¹ photosynthetic photon flux (PPF) and photoperiod of 12 or 24 hours light. Increased CO₂ provided greater tuber yield at low PPF, but decreased tuber yields at high PPF. Increasing the PPF increased the tuber yield for Denali but decreased the yield for Russet Burbank. When averaged across all irradiance treatments, Denali showed the greatest gain in tuber and total weight (21 and 18 per cent, respectively) in response to increased CO₂ enrichment for the three cultivars tested. Norland showed the least (9 per cent for both), while Russet Burbank showed an intermediate response, with gains nearly as great as for Denali under a 12 h photoperiod (18 per cent), but less than Denali under a 24 h photoperiod. A pattern of greater potato plant growth was observed from CO₂ enrichment under lower PPF and a short photoperiod.

Crop-growing systems for space travel are needed to generate oxygen, purify water, remove carbon dioxide, produce food and recycle waste materials. Total irradiance has been suggested to be the largest limitation to crop productivity in these systems. Potato yield improvements might be obtained by increasing the net daily photosynthetically active radiation (PAR) through higher irradiance or longer photoperiod (Stuttle et al., 1996). The photoperiod duration doubles from December to June at 50°N, while PAR increases eightfold, from 211 to 1 701 MJ m⁻² d⁻¹, due to higher elevation of the sun above the horizon with lengthening days. Gross carbohydrate production on standard clear days increases from 108 to 529 kg ha⁻¹ d⁻¹ at 50° N, whereas it remains at about 420 kg ha⁻¹ d⁻¹ year-round near the Equator. Low solar irradiance is a yield constraint at 30° N to 40° N in winter when potatoes are grown to escape the summer heat (Haverkort, 1990).

Stuttle et al. (1996) studied the effect of photoperiod (12, 18, and 24 h light) on net carbon assimilation rate \( A_{\text{net}} \) and starch accumulation in newly mature canopy leaves of Norland potato under low and high PPF, 263 and 412 μE m⁻² s⁻¹,
respectively. Whenever the photoperiod was increased from 12 to 18 hours, there was a marked decline in $A_{\text{net}}$ of 16.1 per cent and declines were most pronounced under high PPF. The maximum starch concentrations were obtained under high PPF treatments at a shorter photoperiod than under low light treatments. An apparent feedback mechanism exists for regulating $A_{\text{net}}$ under high PPF, high CO$_2$ and long photoperiod, but there was no correlation between $A_{\text{net}}$ and starch concentration in individual leaves. This suggests that maximum $A_{\text{net}}$ cannot be sustained with elevated CO$_2$ enrichments under long photoperiod and high PPF conditions for Norland. Therefore, if a physiological limit exists for the fixation and transport of carbon, increasing photoperiod and light intensity under high CO$_2$ enrichment may not maximize potato yield.

Since the onset and early phases of tuber growth are important for the further development of potato, Dam et al. (1996) conducted a factorial experiment with two photoperiods (12 or 18 h) and four 12 h day/night temperatures (18°C/12°C, 22°C/16°C, 26°C/20°C and 30°C/24°C) to analyse photoperiod and temperature effects on early tuber growth, dry matter partitioning and tuber number for cultivars “Spunta” and “Desiree”. They concluded that low mean temperatures (15°C–19°C) with a short photoperiod (12 h) were most suitable for early tuber growth. Under these conditions, onset of growth and onset of bulking were early, and absolute tuber growth rates and dry matter partitioning were high. Slight increases in temperature strongly reduced partitioning rates, whereas further increases had a large impact on the onset of tuber growth and absolute growth rates. Differences between treatments in numbers of tubers initiated were inconsistent. The absolute growth rate under long photoperiod was higher for Spunta than for Desiree. Different genotype responses to temperature and photoperiod in tuber growth were also found by Snyder and Ewing (1989) using potato cuttings.

Midmore and Prange (1992) examined the effects of day/night temperature (33°C/25°C or 20°C/10°C), and 12 h high irradiance (430–450 μE m$^{-2}$ s$^{-1}$ PAR), or 12 h low irradiance (250–280 μE m$^{-2}$ s$^{-1}$ PAR), both with a 6 h photoperiod extension at 6 μE m$^{-2}$ s$^{-1}$, on relative growth rate, net assimilation rate and dry matter production of Solanum goniocalyx cv. “Garhuash Huayro” and DTO–33, a heat-tolerant clone of S. tuberosum x S. phureja. The highest relative growth rate was obtained at low temperature and low irradiance. At high temperature, low irradiance had the opposite effect, producing the lowest net assimilation and relative growth rates. Both tuber number and weight were markedly reduced by high temperature. Low irradiance in combination with high temperature produced virtually no tubers. These data are consistent with field observations that reduced potato growth at high temperatures can be aggravated by lower irradiance. Both leaf area and net assimilation rate are reduced.

Manrique and Bartholomew (1991) carried out a potato genotype x environment experiment on Mount Haleakala, Maui, Hawaii, at three elevations, from 91 to 1 097 m, to assess the performance of four standard temperate cultivars and three heat-tolerant clones in warm to cool temperatures at photoperiods prevailing in the tropics. Dry weight of plant components and total dry weight per plant were measured at tuber initiation, 20 days after tuber initiation and 40 days after tuber initiation. Warm temperatures at 91 m hastened development such that, at tuber initiation, total dry weight per plant was 2 to 4 times greater than at 1 097 m in 1985 and 1986. Tuber dry weight increased significantly at the second two sampling dates with lower temperature at higher elevation. Dry matter partitioning to tubers generally was highly and significantly correlated with temperature, with the optimum of 15°C to 20°C for tuber growth. Potato plants lost their ability to allocate dry matter to tubers at higher temperatures.

Sarquis et al. (1996) stated that the magnitude of the effect of elevated temperatures on potato growth and final yield is determined by an intricate interaction among soil temperature, air temperature, solar radiation and photoperiod duration. Their data extended previous observations of reduction in photosynthesis rate under elevated temperatures. Under field conditions they concluded that a reduced carbon assimilation rate could not explain the yield reduction observed; the temperature effect on assimilation was not as dramatic as it was on growth or yield. Other workers have reported a severe reduction in the rate of assimilation at air temperatures above 30°C under controlled experimental conditions. In such cases, the reduction in the carbon assimilation rate was shown to correlate well with reductions in growth and yield (Ku et al., 1977; Midmore and Prange, 1992). These contrasting results reveal the complexity of plant responses to the combined effects of water and temperature stress, which inevitably occur in association under field conditions.

Thornton et al. (1996) examined the effect of two day/night air temperature regimes (low 25°C/12°C and high 35°C/25°C) on dry matter production of three potato clones (Russet Burbank, Desiree, and “DTO–28”) for five weeks, beginning
two weeks after tuberization, under controlled environmental conditions. Tuber growth rate was more affected by high temperature than was whole plant growth. All clones exhibited a decline in tuber dry matter production at high temperatures compared with low temperatures; however, Russet Burbank exhibited the largest decline. Potato clones varied in partitioning of dry matter to tubers at high temperatures. In addition to carbon assimilation, heat stress reduced tuber yields by affecting several plant processes, such as dark respiration.

Although high temperature stress is a major uncontrolled factor affecting growth, development and productivity of plants, relatively little is known about genetic diversity for heat tolerance in potatoes. Tolerance to heat stress may involve many complex relationships. An adapted genotype must have a diverse and complex combination of genes for tolerance to high temperatures and for superior performance in the field (Tai et al., 1994).

Potato cultivars and clones vary significantly in their ability to tuberize at elevated air temperatures and continuous irradiance. Tibbitts et al. (1992) carried out two experiments under controlled environments to determine the capability of 24 highly productive potato genotypes to tolerate continuous light and high temperature. Six cultivars grew well under continuous light while three cultivars were superior to the others at high temperature. Two cultivars were well adapted to continuous light and high temperature. These evaluations were made after only 56 days of growth, and further assessments should be made in longer-term productivity studies.

For some crop plants, leaf angle can be important for maximizing solar radiation interception. With potato cultivars that intercept as much as 95 per cent of incident solar radiation at a leaf area index of 4, one must question whether alterations in leaf angle would significantly improve light interception. Individual leaves can utilize only 50–60 per cent of incident radiation on a clear day. Following tuber initiation, the photosynthetic apparatus saturates by about 1 200 μE m⁻² s⁻¹, or about 60 per cent of full light. Ideally, the top leaves of a potato canopy should absorb no more than 1 200 μE m⁻² s⁻¹ and should allow the remaining light to pass to the lower canopy (Dwelle, 1985). Opportunities remain to modify potato plant architecture to increase productivity (Hawkins, 1982).

Gawronska and Dwelle (1989) studied the effect of high light levels (with maxima between 500 and 1 200 μE m⁻² s⁻¹) and shaded low light levels (approximately one quarter of the high light) on potato plant growth, biomass accumulation and its distribution. They observed that plants under low light did not produce auxiliary shoots, while those under high light did. Tubers of plants under low light were very small and irregular in shape. The most evident plant response to low light was greater stem elongation, as well as a reduction in total biomass accumulation and in tuber weights. The reduction in total biomass under low light was 34 to 45 per cent. Reduction in tuber dry weights under low light ranged from 39 to 57 per cent, depending on the growth stage and harvest time. In addition, at all growth stages, the percentage of biomass partitioned to the tubers was higher under high light than under low light conditions.

According to Gawronska et al. (1990), potato plants grown under low light generally had lower rates of photosynthesis (when compared with those grown under high light), reaching saturation for maximum photosynthesis at about 500 μE m⁻² s⁻¹. Some clones maintained the higher rates of photosynthesis compared to Russet Burbank at nearly all light levels, demonstrating the potential to breed for cultivars that maintain higher rates of photosynthesis and potentially higher tuber yields.

10.5.2.2 Soil temperature and soil temperature management

The rate of development of sprouts from planted seed pieces depends on soil temperature. Very little sprout elongation occurs at 6°C. Elongation is slow at 9°C and is maximized at about 18°C. The time between planting and emergence depends on soil temperature. Phytotron and field experiments carried out by Sale (1979) showed that emergence was linearly related to mean soil temperature and relatively independent of diurnal fluctuations up to an optimum of 22°C–24°C. Up to this optimum, emergence could be considered as a degree-day requirement calculated either from soil temperature at tuber depth or air temperature. At temperatures above the optimum, emergence was inhibited.

Sattelmacher et al. (1990) studied the effect of 20°C and 30°C root-zone temperatures on root growth and root morphology of six potato clones. Significant genotypical differences in the responses of potato roots to 30°C were observed, indicating the potential for selecting heat-tolerant potato clones. In both heat-tolerant and heat-sensitive clones, the size of the root system was reduced by a 30°C root-zone temperature, which can be explained by a reduction in the cell division followed by cessation of root elongation.
Tuberization stimulus favours both tuber initiation and tuber enlargement. Through artificially prolonged exposure to short days and cool temperatures, it is possible to attain such a high level of stimulus that induction is irreversible, even if potato plants are subsequently exposed to long days for weeks or months. The optimum soil temperature for initiating tubers ranges from 16°C to 19°C (Western Potato Council, 2003).

Reynolds and Ewing (1989) examined the influence of four air and soil day/night temperature treatments on root, shoot and tuber growth in growth chambers: cool air (19°C/17°C), with cool or heated soil (20°C/18°C or 32°C/31°C); and hot air (34°C/30°C), with hot or cooled soil (32°C/27°C or 19°C/17°C). Cooling the soil at high air temperatures neither relieved visible symptoms of heat stress on shoot growth nor increased the degree of induction tuberization by the leaves. Heating the soil at cool air temperatures had no apparent detrimental effect on shoot growth or induction of tuberization by the leaves. Under high soil temperatures, stolonization was substantially compromised and there was no underground tuber development. In one experiment, stolons grew up out of the hot soil and formed aerial tubers above the soil surface in the cool air. The induction of tuberization by the leaves was affected mainly by air rather than soil temperature, but the signal to tuberize might be blocked by high soil temperatures. According to Mares et al. (1985), it is expected that the effect of high soil temperature on growing tubers would be similar to that of exogenously applied gibberellin, inhibiting tuberization.

Tuber development declines as soil temperatures rise above 20°C and tuber growth practically stops at soil temperatures above 30°C. The number of tubers set per plant is greater at lower temperatures than at higher temperatures, whereas higher temperatures favour development of large tubers (Western Potato Council, 2003).

Little research is available on the effect of soil temperature during tuber growth on potato grade and quality. Kincaid et al. (1993), assessing the influence of the interaction between water management and soil temperature on potato quality in the Pacific Northwest region of the United States, observed that the critical period for tuber quality appears to be from mid-June to mid-July, based on measured soil temperature differences, and that frequent sprinkler irrigation reduced soil temperatures, along with the incidence of sugar-end tubers. Yamaguchi et al. (1964) found that yield, specific gravity and starch content of Russet Burbank and “White Rose” tubers were higher and the sugar content lower when grown at soil temperatures between 15°C and 24°C, than when grown at higher temperatures.

Ewing (1981) reports that in many areas the sequence of temperatures that most often brings economic damage to potato crops is warm temperatures early in the season, followed by cool temperatures that induce strong tuberization, followed in turn by another period of high temperatures. These temperature oscillations lead to heat sprouts, chain tubers and secondary growth of tubers. Apparently, the fluctuations in tuberization stimulus cause tuber formation to alternate with more stolon-like growth.

Management practices such as planting population density, use of mulch and irrigation might substantially modify the soil temperature regime within the root zone in such a way as to affect stolonization and tuber initiation, bulking and enlargement at a given site, particularly where solar irradiance availability is shown to be a non-limiting factor for potato production. Increase of plant population through a reduction in between-row spacing was effective in raising tuber yields in the hot tropics, largely through the increase in amounts of intercepted solar radiation, which brought about a significant decline in soil temperatures during the tuber growth. Since the proportion of marketable tubers was scarcely affected by planting densities, Midmore (1988) reasoned that potato plant population in hot climates should be as high as possible without limiting the amount of soil available for hill-up.

In order to quantify the effects of organic mulch on soil temperature and soil moisture regimes during the growth of potato, Midmore et al. (1986a) conducted seven experiments at three contrasting hot tropical sites (latitude varying from 5°S to 12°S, and altitude ranging from 180 to 800 m). Mulch retained more heat in the soil at night when combined with agronomic practices that themselves increased soil heat retention at night (that is, on the flat potato beds). The magnitude of soil cooling by mulch during the day and heat retention within the soil at night was dependent on solar irradiance levels and soil moisture content. Mulch was more effective in cooling dry soils, especially at high irradiance. Heat retention at night following days of low irradiance was greater in mulched plots, whereas at high irradiance heat retention of mulched plots was intermediate between those of moist and drier control plots.

Midmore et al. (1986b) showed that mulch increased tuber yield by 20 per cent during the summer in Lima, Peru. Manrique and Meyer (1984), studying...
the impact of mulches on potato production during winter and summer seasons at the same site, found no effect on yields during the winter, but yield increases of 58 per cent and improvements in soil moisture retention were obtained in the summer with surface mulch.

Mahmood et al. (2002) reported that mulch at Islamabad, Pakistan, decreased daily maximum soil temperature at a 15 cm depth by 1.5°C to 4.5°C, resulting in faster emergence, earlier canopy development and higher tuber yields. Many other recent studies conducted in Asia point out the beneficial effects of mulch in potato production systems as an efficient alternative to obviate heat and water stresses in order to maximize crop yield (Jaiswal, 1995; Ruiz et al., 1999; Sarma et al., 1999).

10.5.2.3 Atmospheric humidity, wind and wind management

There are very few recent studies dealing with the direct effects of relative humidity (RH) on potato growth, tuber yield and grade. Most of the contributions related to the influence of RH on potato refer to potato storage where RH is an important factor in tuber weight loss and the occurrence and severity of diseases and pests. The same scarcity of research exists with regard to the wind regimes at a particular location as an agrometeorological factor affecting potato production systems.

Wheeler et al. (1989) studied the effect of two RH levels, 50 per cent and 85 per cent, on the physiological responses of three cultivars of potato (Russet Burbank, Norland and Denali) in controlled-environment rooms under continuous light intensity at 20°C. No significant differences in total plant dry weight were measured between the atmospheric humidity treatments, but plants grown under 85 per cent RH produced higher tuber yields. Leaf areas were greater under 50 per cent RH and leaves tended to be larger and darker green under drier atmospheric conditions than at more humid conditions. The elevated humidity appeared to shift the allocation pattern of photosynthates to favour allocation to the tubers over leaves and stems.

Gordon et al. (1999) estimated sap flow from solar radiation and vapour pressure deficit data for three field-grown potato cultivars ("Atlantic", "Monona" and "Norchip") at Nova Scotia, Canada, under non-limiting soil water conditions. Sap flow rates for all cultivars were closely linked with solar radiation under conditions where soil water was not limiting. The vapour pressure deficit (VPD), a function of relative humidity and air temperature, had less effect on sap flow, although the magnitude of the VPD during the growing season was generally < 2 kPa. All cultivars maintained actual daily transpiration near the potential energy-limiting rate under well-watered conditions. When the soil was drier (per cent available soil water <30 per cent), Monona potato plants had a much more rapid decline in transpiration than the other two cultivars.

Another physiological parameter closely related to yield is water use efficiency. Bowen (2003) reported that potato farming in coastal Peru occurs during the winter, when the cool humid conditions favour growth and promote a more efficient use of irrigation water. During the winter, less soil water evaporation caused by a smaller VPD enhances water use efficiency when compared with that observed during the summer. Sinclair (1984) also showed that generally more humid environments provide greater water use efficiency because of a lower VPD.

Stomatal resistance governs photosynthesis and transpiration. Two major feedback loops are reported by Raschke (1979) as the direct controllers of stomatal resistance ($r_{st}$). The first involves photosynthesis, where a reduction in intercellular CO$_2$ occurs as PAR increases, the stomata open and $r_{st}$ decreases. The second involves an increase in $r_{st}$ whenever leaf water potential reaches a critical threshold as a result of transpiration intensity.

Stomatal resistance is affected by many factors, including PAR, the ratio of leaf to air water potential, leaf age, air temperature and the ambient CO$_2$ concentration (Kim and Verma, 1991). Gordon et al. (1997) studied the stomatal resistance of three field-grown potato cultivars (Atlantic, Monona and Norchip) in response to photosynthetic photon flux density, leaf-to-air vapour pressure difference and root-zone available water. Under the climatic conditions of their field experiment in eastern Canada, stomatal activity in potato was primarily driven by light intensity. As soil water became limiting, however, the soil/plant water status became increasingly more important. The absence of very high VPD values throughout the growing season is the probable main reason for the lack of potato $r_{st}$ response to air vapour pressure differences. Significant differences were observed among cultivars in the response of stomata to changes in available soil water. Crop weather modelling needs to incorporate these differences into model systems because they might have a significant effect on eventual model performance at a given site.

Wind has important effects on potato. Pavlista (2002) reported that leaves injured by lower wind speeds
show bronzed areas, brown with a shiny surface, due to the rubbing of leaves against each other. The bronzed areas tend to become brittle from drying. When pressed, the bronzed areas crack, forming a sharp-edged rip through the affected tissue. Under higher wind speeds, leaves not only bronze but also tatter. Tattered leaves typically have tears measuring 6 to 25 mm with irregular brownish borders. Stems may also be affected by winds. When exposed to a mild wind, stems may just be flopped around, causing a slight weakness of the tissues. Under strong winds, vines might actually get twisted, bringing about a break or hinge-like weakness in the stems. If exposed to strong winds for several hours, the vine may twist all the way around and cause the stem to collapse, cutting off nutrient flow through the phloem between the vine and the tubers.

Wind also affects transpiration rates and, therefore, photosynthetic activity and crop yield. At sites where winds are frequently strong throughout the year, increased stomatal resistance can cause reduction in potato yield (Pavlista, 2002; Sun and Dickinson, 1997). At such sites, guidelines for the sustainable management of potato cropping systems need an emphasis on windbreak development, including height, porosity and orientation.

Sun and Dickinson (1997) studied the benefit of two 30-month-old windbreaks (one with two rows of trees and one with three rows of trees) for potato in tropical north-eastern Australia. Two Eucalyptus species (E. microcorys and E. torelliana) were found to be highly suitable for windbreaks since they showed rapid development in height and branch growth while retaining low branches. The porosity of three-row and two-row windbreaks was 37.2 per cent and 60 per cent, respectively. The optimum range of porosity for windbreaks is between 40 and 50 per cent (Marshall, 1967). Windbreaks increased potato plant growth in height and leaf number; they had limited effects on leaf length and width, however. Potato plants grown close to windbreaks yielded more than those grown at the farthest positions, with the highest production reported at a distance of three times the windbreak height. Windbreaks increased potato yield by up to 7.7 per cent, whereas Sturrock (1981) found windbreaks increased yield by 35 per cent.

Wright and Brooks (2002) examined the effect of windbreaks on growth and yield of potatoes over a four-year period in Australia, measuring the amount and severity of wind damage to leaves, plant height and leaf numbers on potato located at various distances from the windbreak in both sheltered and unsheltered positions. Windbreaks increased tuber yield between 4.8 and 9.3 per cent for the sheltered portion of the field in seasons with higher than average wind speeds and caused a reduction in wind damage to leaves on protected potato plants. In seasons when wind speed was above average, windbreaks increased yield at distances away from the windbreak between 3 and 18 times the height of the windbreak. Cleugh (2003) reported that potato crop yields were significantly higher in the sheltered zone ranging from 2 to 18 times the height of the windbreak, compared with yields obtained in unprotected areas.

### 10.5.2.4 Crop evapotranspiration and irrigation requirements

Crop consumptive water use is the amount of water transpired by the plants, plus the water evaporated from the soil, plus the fraction of water held by the plant tissues. The amount of water retained by plant metabolic activity is about 1 per cent of the overall water taken up by the plants. Thus, in practical terms crop water consumption corresponds to crop evapotranspiration (ETc). Potato ETc can be estimated using weather data and is the amount of water to be replenished during the growing season in order to assure potential tuber yields at a given site. Potato ETc is important to consider in irrigation planning and its use in irrigation scheduling is a well-developed strategy to improve the effectiveness of irrigation.

An adequate water supply is required from tuber initiation up until near maturity for high yield and good quality. Applying water in excess of plant needs compromises the environment, may harm the crop and is expensive for growers. Excessive irrigation of potatoes results in water loss and significantly increases runoff and soil erosion from production fields to rivers, streams and reservoirs. Leaching can lead to contamination of the groundwater due to lixiviation of fertilizers and other chemical products (Al-Jamal et al., 2001; Feibert et al., 1998; Shock et al., 2001; Waddell et al., 2000). Irrigation in excess of crop needs increases production costs, can reduce yield by affecting soil aeration and root system respiration, and favours the occurrence and severity of diseases and pests. Deficient irrigation promotes a reduction in tuber quality and lower yield due to reduced leaf area and/or reduced photosynthesis per unit leaf area (van Loon, 1981).

Local atmospheric conditions, surface soil wetness, stage of growth and the amount of crop cover are the factors that govern the daily fluctuations of potato ETc as reported by Wright and Stark (1990). They observed that ETc increased as the leaf area...
and transpiration increased and reached near-maximum levels just before effective full cover. The LAI reached 3.5 by effective full cover coincident with the highest daily ET$_c$ of 8.5 mm. Seasonal total ET$_c$ corresponded to 604 mm in southern Idaho (United States).

Potato ET$_c$ varies greatly from region to region. Seasonal potato ET$_c$ in the humid Wisconsin area for June through August ranged from 293 to 405 mm during three years of study (Tanner, 1981). At Mesa, Arizona, ET$_c$ for February through June averaged 617 mm (Erie et al., 1965). The mid-season daily potato ET$_c$ was 6 mm near Calgary, Alberta, in Canada (Nkemdirim, 1976), while the daily water consumption was 3 mm under the climatic conditions of Botucatu, in the state of São Paulo, Brazil, during the winter, with a seasonal ET$_c$ of only 283 mm (Pereira et al., 1995a). Wright and Stark (1990) reported that seasonal water use in irrigated areas of Oregon and Washington (United States) ranged from 640 to 700 mm. For high yields at a given site, the seasonal water requirements of a potato crop with a phenological cycle varying from 120 to 150 days ranged from 500 to 700 mm, depending on climate (FAO, 1979).

The maximum daily potato ET$_c$ measured by a weighing lysimeter in a sub-humid region in India was found to be 4.24 mm d$^{-1}$ (Kashyap and Panda, 2001). Under a hot and dry climate in north-eastern Portugal, peak ET$_c$ rates reached 12−13 mm d$^{-1}$ on the days immediately following irrigation, but crop water use declined logarithmically with time to about 3 mm d$^{-1}$ within five days (Pereira and Carr, 2002).

Wright (1982) developed improved crop coefficients for various irrigated crops in the Pacific North-west of the United States, including potato, using alfalfa to measure reference evapotranspiration (ET$_{ro}$) and weighing lysimeters at an experimental field near Kimberly, Idaho. Growth-stage-specific crop coefficients (K$_c$) and the water balance method provided a valuable tool in scheduling overhead irrigation of Russet Burbank potatoes in the Columbia Basin of Oregon (Hane and Pumphrey, 1984). Simonne et al. (2002) reported that K$_c$ values ranged from 0.3 at emergence to 0.8 during maximum leaf area, and declined as the crop matured. ET$_c$ is usually calculated by the product of K$_c$ and ET$_{ro}$, or as a function of a number of climatic elements, to provide the atmospheric potential demand.

Apart from the crop coefficient approach, potato evapotranspiration can also be estimated by means of multiple regression equations that take into consideration the LAI of potato crop and atmospheric evaporative demand depicted by ET$_{ro}$ or pan evaporation (Pereira et al., 1995b).

Potato can be sensitive to irrigation at levels that are less than ET$_c$, and that result in soil water deficits. A study in three successive years on silt loam soil in eastern Oregon investigated the effect of water deficit on yield and quality of four potato cultivars grown under four season-long sprinkler irrigation treatments (Shock et al., 1998). The results suggest that irrigation water applied at rates less than ET$_c$ in the Treasure Valley of Oregon would not be a viable management tool to economize water, because the small financial benefit would not offset the high risk of reduced tuber yield and profit from the reduced water application.

Potato cultivars may respond differently not only to deficit irrigation but also to total seasonal crop evapotranspiration under non-limiting soil water supply. Wolfe et al. (1983) reported that total seasonal actual crop water use at Davis, California, on a deep Yolo loam soil ranged from 316 to 610 mm for the “Kennebec” cultivar and from 331 to 630 mm for “White Rose”, as a function of six levels of irrigation water supply established throughout the growing season. Shock et al. (2003a), comparing the performance of two new potato cultivars (“Umatilla Russet” and “Russet Legend”) with four other cultivars grown in the Treasure Valley of Oregon (“Russet Burbank”, “Shephody”, “Frontier Russet”, and “Ranger Russet”), observed that Umatilla Russet showed a higher yield potential at ideal water application rates, while Russet Legend was the only cultivar tolerant to deficit irrigation treatments.

ET$_c$ is an essential agrometeorological index that can be used to determine both the amount of water to be applied and the irrigation frequency for a particular crop and site. Stöckle and Hiller (1994) compared a canopy temperature-based method, the neutron probe method and the computer-assisted method on the basis of evapotranspiration and K$_c$ values to schedule irrigation for potato in central Washington State. A soil water depletion of 70 per cent was allowed before starting irrigation. They concluded that the most practical method was the computer-assisted method using estimates of ET$_{ro}$ and K$_c$ values.

10.5.2.5 **Soil moisture requirements and irrigation management**

Soil moisture status is expressed by per cent available soil water (ASW) content or by soil water tension.
(SWT). Available soil water content is defined as the amount of water that plants can extract from a given volume of soil, from the crop effective rooting zone. Available soil water is usually expressed as a percentage between “field capacity” (100 per cent) and “permanent wilting point” (0 per cent). Soil water tension is the force necessary for roots to extract water from the soil.

Curwen (1993) reviewed water management for potato and placed great emphasis on using the irrigation criterion of 65 per cent ASW. At “field capacity” (100 per cent ASW), the SWT is often between 20 and 33 kPa, depending on soil type and the method of determination. Soil water is assumed to no longer be available at the “permanent wilting point”, generally assumed to be at a SWT of 1 500 kPa.

The ASW approach works well for irrigation scheduling in regions with extensive areas of homogeneous soil. It is often a practical impossibility for growers to know when the soil is at 65 per cent ASW, even if they have soil water content sensors available. Usually the per cent water content that a given field contains at “field capacity” is unknown for a given part of a specific field. Similarly, the percentage of water content at the “permanent wilting point” for a given part of a specific field is also usually unknown. Both the “field capacity” and the “permanent wilting point” vary tremendously with soil type, from spot to spot within a field, with cultivation and over time. With neither “field capacity” nor “permanent wilting point” known, 65 per cent ASW cannot be known; the prescription of an irrigation criterion of 65 per cent ASW can become much like telling a grower to irrigate at the “right moment” and leaving the decision to intuition and experience.

Growers need direct and unambiguous irrigation recommendations to deal with crops that have negative responses to small variations in irrigation management. In contrast to the ASW, SWT can be measured directly using tensiometers or granular matrix sensors (Shock, 2003). The SWT irrigation criterion needed to optimize potato yield and quality can be determined by production region and generalized soil type.

Measurements of SWT that optimize potato yield and grade have been determined for a number of locations, some of which are wetter than 65 per cent ASW. Based on potato yield and grade responses to irrigation, ideal potato SWT irrigation criteria were found to be 50 kPa using furrow irrigation on loam in California (Timm and Flockner, 1966), 50 to 60 kPa using sprinklers on silt loam in Oregon (Eldredge et al., 1992, 1996), 25 kPa using sprinklers on silt loam in Maine (Epstein and Grant, 1973), 60 kPa and 30 kPa using furrow and drip irrigation, respectively, for silt loam in Oregon (Shock et al., 1993, 2002), and 20 kPa using sprinklers on sandy loam in Western Australia (Hegney and Hoffman, 1997).

### 10.5.2.6 Irrigation scheduling

Irrigation of crops sensitive to water stress requires a systematic approach to irrigation scheduling. Information to answer irrigation scheduling questions may include atmospherically based, plant-based or soil-based data (Heerman et al., 1990; Shae et al., 1999). Examples of atmospheric irrigation scheduling information include weather forecasts, estimates of crop evapotranspiration, such as those provided by AgriMet (United States Bureau of Reclamation, Pacific North-west agricultural meteorological stations), pan evaporation and atmometers. AgriMet is an automated weather station network operating throughout the Pacific North-west of the United States that uses site-specific climatic data, the current stage of growth of local crops and models to estimate daily crop water use (Pereira and Shock, 2006). Access to daily weather data, crop water use charts and related information is available at http://www.usbr.gov/pn/agrimet.

Plant data may include canopy temperature, xylem water potential and visible wilting. Soil-based data may include soil water content and soil water tension. In practice, plant, soil and atmospheric data are often used concurrently, especially when changes in irrigation schedules are required to adjust for changes in crop water use.

Growers should pay attention to crop appearance, soil water tension, the rate of crop evapotranspiration, precipitation and the amount of water applied. With knowledge of these factors, irrigation can be well managed in order to obtain high yields of better-quality tubers, along with environmental protection (Pereira and Shock, 2006).

### 10.5.3 Other background information on potato (yield, quality) response to irrigation management

Potato tuber response to soil moisture conditions begins before tuber set. MacKerron and Jefferies (1986) have shown that increased duration of water stress before tuber initiation reduces tuber set per stem. Shock et al. (1992) demonstrated that reduced tuber set in the Treasure Valley was related to the duration of SWT drier than 60 kPa before and
during the beginning of tuber set. Where Verticillium wilt is present, there are advantages to keeping soils a little dry early in the season before tuber initiation (Cappaert et al., 1994; Shock et al., 1992).

Jones and Johnson (1958) described the reduction in potato yield caused by water stress. Through the use of a line-source sprinkler system, Hang and Miller (1986) showed how a moisture gradient affects plant-top growth, tuber yield and tuber grade. With sprinkler irrigation, water application had to remain near potential ET<sub>c</sub> for maximum tuber yield and grade.

Potato varieties differ in their response to water stress (Shock et al., 2003a). Kleinkopf (1979) found that Russet Burbank was more sensitive than the “Butte” variety in forming misshapen tubers under water stress.

10.5.3.1 Assuring tuber grade

Fluctuations in water that stress the potato plant during tuber development can result in greater proportions of misshapen tubers of lower market grade. Corey and Myers (1955) determined that the proportion of misshapen tubers was directly related to drier SWT. Eldredge et al. (1992) found that a single transient SWT stress drier than 50 kPa increased misshapen Russet Burbank tubers. Pereira and Villa Nova (2002) studied the effect of three irrigation treatments on tuber yield and grade at Botucatu, São Paulo, Brazil. Potatoes irrigated to fully replace ET<sub>c</sub> had higher yields and better grade and fewer physiological defects.

10.5.3.2 Assuring internal tuber quality

Tuber physiological disorders such as brown centre, hollow heart and translucent end, as well as secondary growth, growth cracks, bruise susceptibility and heat necrosis, have been associated with water stress and/or wide variations in soil moisture content (Eldredge et al., 1992, 1996; Hooker, 1981; Hiller et al., 1985; MacKerron and Jefferies, 1985; Rex and Mazza, 1989; Shock et al., 1993).

The sugar-end disorder is also known as dark ends, translucent ends, or in more severe incidences when stem-end tissue breakdown occurs, jelly ends. Jelly ends can occur in the field or during storage. These physiological disorders are often considered a minor production problem. When above-normal temperatures occur during the growing season, however, significant economic losses can result from excess reducing sugars (glucose and fructose) in the stem end of tubers. These reducing sugars react with free amino acids during frying to form brown or black colours. For processors, dark ends result in reduced processing efficiency and profitability and in some cases, an unusable product (Valenti, 2002).

When dark ends, as measured at harvest, exceed contract specifications, grower returns are reduced by contract penalty clauses. Research has shown that the incidence of sugar ends in tubers was reduced substantially when irrigation scheduling was based on SWT measurements (Eldredge et al. 1996; Shock et al., 1993). Dark ends may become more severe after tubers have been stored (Eldredge et al., 1996). The timing of water stress is important; water stress before tuber initiation has no deleterious effect on tuber quality (Shock et al., 1992), while stress later during tuber bulking can cause dark stem-end fry colour and reduced specific gravity (Eldredge et al., 1992, 1996; Shock et al., 1993).

Penman (1929) was one of the first authors to discuss the importance of translucent-end potatoes. Numerous authors have suggested that translucent-end potatoes are caused by early-season moisture stress (Murphy, 1936; Nielson and Sparks, 1953; Kunkel, 1957; Kunkel and Gardner, 1958; Lupt, 1960). Iritani and Weller (1973a, 1973b) and Iritani et al. (1973) produced translucent-end potatoes by subjecting plants grown in Washington to two weeks of moisture stress in late June.

Sugar-end tubers result in French fries with “dark ends” and are related to tubers with translucent ends and jelly ends. Owings et al. (1978) reproduced the results of Iritani and Weller (1973a), demonstrating that late-June water stress could cause sugar ends. Shock et al. (1992) subjected potatoes to water stress in May and the beginning of June and found that stress very early in the season did not result in sugar ends. But short-duration water stress any time during tuber bulking, accompanied by heat stress, resulted in sugar ends (Shock et al., 1993).

Increases in reducing sugars occurred more than two weeks after the end of transient water stress (Shock et al., 1993; Eldredge et al., 1996), which suggests that water stress causes enzymatic or membrane changes that eventually result in the loss of cellular control of sugar metabolism and the onset of sugar ends and translucent ends. Sowokinos et al. (2000) demonstrated the importance of specific tuber starch and sugar enzymes in the development of sugar ends.

Paradoxically, season-long uniform stress does not have the same negative effect on potato tubers.
Painter et al. (1975) observed no fry colour differences between tubers irrigated at 25 ASW throughout the season and those irrigated at 65 ASW, which proved to be consistent with later findings where potato was stressed all season (Shock et al., 1998, 2003a). Kleinkopf (1979), Iritani and Weller (1977), Shock et al. (1993) and other researchers have demonstrated that reducing-sugar concentrations vary among varieties.

Kincaid et al. (1993) reviewed the role of temperature on tuber development and demonstrated that sugar ends are increased by rises in soil temperature. The relative roles of water stress and temperature stress on potato defects are poorly defined. Water stress is often associated with increased canopy temperature and soil heating in the field. In most field trials where water stress has been imposed and measured, canopy and soil temperatures have not been measured.

10.5.4 Other management aspects of potato (irrigation and microclimate interaction with potato diseases and pests)

Irrigation management practices can affect disease severity. The increased humidity from irrigation will have greater effects where the macroclimate is humid or sub-humid and will be of less importance where it is drier. For potato grown in hot areas, sprinkler irrigation can cool the environment, with possible reductions in physiological defects. Different irrigation methods, however, can contribute to the occurrence of diseases and pests on the crop depending on site-specific weather patterns.

Wet soil is conducive to most tuber-rotting pathogens. Excessive soil moisture following planting can promote seed-piece decay and erratic plant development. Excess soil moisture also encourages the incidence of blights, rots and wilts, and this is particularly true of prolonged excess soil water conditions.

Avoiding over-irrigation, or even keeping soils a little dry early in the season before tuber initiation, may reduce the amount of root infection by V. dahliae, a major component in early die. On the other hand, avoiding excessive plant water stress during the tuber bulking growth stage, which usually coincides with the warmest part of the season, may help decrease the severity of early die (Cappaert et al., 1994).

Potato vines that remain wet for long periods create a micro-environment conducive to early blight (Alternaria solani), late blight (Phytophthora infestans), white mold (Sclerotinia sclerotiorum) and blackleg (Rhizoctonia solani) (Curwen, 1993). The timing of these diseases and associated crop losses vary regionally with yearly weather patterns, and can be affected by irrigation methods, which increase or decrease the duration of high humidity in the crop canopy.

Consistently rainy summer or fall weather promotes late blight. In the 1990s, however, epidemics of late blight developed in potato crops in arid production areas of the Pacific North-west region of the United States where late blight had not been a problem (Stevenson, 1993). Irrigation that tends to keep the foliage wet may contribute to this developing risk. Potatoes cultivated under centre-pivot irrigation can receive a relatively low volume of irrigation water for a long time near the pivot, favouring late blight occurrence. Johnson et al. (2003) showed that the incidence of late blight tuber rot grew significantly as the application of irrigation water increased, and was significantly greater within 30 m of the pivot than at greater distances. Long-duration sprinkler irrigation also favoured late blight in Oregon and California (Shock et al., 2003b). Cohen et al. (2000) showed that under overhead sprinkler irrigation, the proportion of potato leaflets containing late blight oospores and the number of oospores per leaflet were dependent on the soil water regime (rain plus sprinkler irrigation).

Long periods of leaf wetness or high relative humidity within the potato canopy favour infection by white mold (Powelson et al., 1993). Avoiding light, frequent irrigation of coarse-textured soils, and avoiding heavy, less frequent irrigation of fine-textured soils can diminish the risk of white mould.

Simons and Gilligan (1997) found irrigation to increase the incidence of stem canker, stolen canker and black scurf to a limited extent, although the effect of season tended to be more pronounced on these defects than any of the agronomic treatments tested.

While the development of high humidity in the canopy is to be avoided, adequate soil moisture is essential not only for potato yield and quality, but also for pest management strategies. Adequate soil moisture helps reduce the attack of cutworms (Spodoptera litura) and mites (Tetranychus spp. and Tenuipalpidae spp.). Potato tubermoth (Phthorimaea operculella) and its larvae are repelled by soil moisture. Soil moisture also reduces formation of cracks in the soil, which allow the entry of potato tubermoth and its larvae (Grewal and Jaiswal, 1990). Irrigation scheduling based on ETc and/or SWT can take the
local climate into account and keep the soil from becoming too dry.

10.6. AGROMETEOROLOGY AND RICE PRODUCTION

10.6.1 Importance of rice in various climates

The cultivation of rice has been practised in many countries for over 6,500 years. Dryland rice culture preceded the adoption of wetland paddy culture. Two species of the rice genus have been domesticated: *Oryza sativa* and *Oryza glaberrima*. The former is widely cultivated and originated in the foothills of the Himalayas, while the latter, limited to Africa, originated in the Niger River delta. Rice is the most important cereal grain for human consumption, meeting the needs of 50 per cent of the world’s population. The agricultural and industrial uses of rice include the use of rice straw and bran as cattle feed and as a growing medium for mushrooms; use of rice husks and hulls as a seedbed medium; use of bran for extraction of a healthful oil; and use of rice for making rice beer and rice-based wine. Only 5 per cent of the total global production of rice enters international trade. Thus, for many countries national self-sufficiency in rice production is a crucial matter.

Rice is grown from about 50° N to 35° S and from below sea level to above 2,000 m, covering a mean temperature range of 17°C to 33°C, a growing-season rainfall range of 0 to 5,100 mm, and a solar radiation range of 300 to 600 calories/cm²/day in the various growing areas and different seasons. Many of the rice-growing areas are served by major rivers and have alternating wet and dry seasons. The varieties used and cultural practices adopted in rice cultivation vary widely and are influenced by local climatology (rainfall, temperature and solar radiation regimes) and times and certainty of availability of water for main or supplementary surface irrigation. The variations in cultural practices may not, per se, affect the phenological or physiological responses of the crop to weather factors. The water, fertilizer and seed requirements of the crop, its field-life duration, extent of realization of potential yields, and susceptibility to pests, diseases and weeds are affected by cultural practices, however. The unravelling of the relationship between weather and various aspects of growth, development, yield and protection of rice crops is, therefore, complex.

Data on production, acreages and per capita consumption of rice for 29 countries that produce more than one million tonnes of rice are set out in Table 10.6.1. Of the total 620 million tonnes of global rice production, the 29 countries in the list account for about 580 million tonnes, with an average yield of 3.9 tonnes per hectare (t/ha). The following points are evident from Table 10.6.1. Nearly 90 per cent of the rice is produced in Asia. China and India account for 30 per cent and 20 per cent of global production, and 20 per cent and 30 per cent of the global cultivation area, respectively. The South-East Asian region extending from Pakistan to Indonesia and comprising 12 countries accounts for 60 per cent and 70 per cent, respectively, of the global area and production. In this region, rice yield averages 3.5 t/ha, with Indonesia and Viet Nam producing 4.5 t/ha and Cambodia and Thailand producing 2 t/ha and 2.5 t/ha, respectively. The yields in Egypt and Australia are 10 t/ha and 8 t/ha, respectively, while the yield in China, Italy, Japan and the Republic of Korea is in the range of 6 to 7 t/ha. Thus, a poleward increase in rice yields is discernible. The yields in African regions are very low and range from 1 to 2 t/ha.

It is estimated that rice production must increase by at least 40 per cent in the coming three decades to meet the global requirements. Over most of the regions, rice yields are beginning to decline. Irrigation can push up rice yields. But because of the substantial non-crop use, water losses in irrigated, puddle rice cultivation, and its very low water use efficiency, a shortage of surface irrigation available for catering to even current areas of puddled rice culture is a certainty in the future. The immediate need is, therefore, to increase gross rice acreage and out-turns through the optimal use of existing resources. In this context, the practice of growing irrigated rice under puddled conditions deserves critical examination.

10.6.1.1 Importance of rice in tropical Asia

Both the South-East and East Asian regions regularly experience cyclonic storms/typhoons, are subject to riverine floods, and are characterized by heavy rains of 100 mm per week or so over an extended period. Rice is the only suitable crop that can be grown under puddled soil conditions, that is, with standing water over bunded fields. In fact, certain varieties of rice, called floating rice, have the ability to elongate their stems with a rise in water level up to a height of 2 m and remain alive for a fortnight even when water levels reach a height of 6 m. The low yield in the South-East and East Asian regions is due to the preponderance of rainfed areas, which also leads to great interannual variability in out-turns. There are vast rice-growing areas in populous countries of
Table 10.6.1. Rice production and consumption statistics worldwide, 2002
(FAOSTAT service; http://faostat.fao.org)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (000 tonnes)</th>
<th>Area (000 ha)</th>
<th>Yield (t/ha)</th>
<th>Consumption (kg/capita/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>176 342</td>
<td>28 509</td>
<td>6.19</td>
<td>83</td>
</tr>
<tr>
<td>India</td>
<td>116 500</td>
<td>40 280</td>
<td>2.89</td>
<td>83</td>
</tr>
<tr>
<td>Indonesia</td>
<td>51 490</td>
<td>11 521</td>
<td>4.47</td>
<td>149</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>37 593</td>
<td>10 771</td>
<td>3.49</td>
<td>164</td>
</tr>
<tr>
<td>Viet Nam</td>
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<td>7 504</td>
<td>4.59</td>
<td>169</td>
</tr>
<tr>
<td>Thailand</td>
<td>26 057</td>
<td>9 988</td>
<td>2.61</td>
<td>103</td>
</tr>
<tr>
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<td>6 381</td>
<td>3.42</td>
<td>205</td>
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<tr>
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<td>3.28</td>
<td>105</td>
</tr>
<tr>
<td>Japan</td>
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<td>58</td>
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<tr>
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<td>3 146</td>
<td>3.32</td>
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<tr>
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<tr>
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<td>49</td>
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<td>Ecuador</td>
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</tr>
<tr>
<td>Australia</td>
<td>1 192</td>
<td>150</td>
<td>7.95</td>
<td>10</td>
</tr>
<tr>
<td>Côte d’Ivoire</td>
<td>1 080</td>
<td>470</td>
<td>2.30</td>
<td>63</td>
</tr>
<tr>
<td>World</td>
<td>577 971</td>
<td>147 633</td>
<td>3.91</td>
<td>57</td>
</tr>
</tbody>
</table>

Yield = Total production/total area and an average across all rice environments and seasons.
tropical Asia. Puddled rice culture is labour-intensive and hence suited to the regions mentioned, which have low labour costs. Puddled rice is said to be of assistance in mitigating the effects of floods. The problem of weeds is minimal in puddled rice culture. Thus rice serves as a livelihood crop for millions of small, marginal farmers in tropical Asia who can afford only low-cost technologies.

10.6.2 **Agroclimatology of rice**

10.6.2.1 **Rice production ecosystems and main climate-related problems**

The main systems of rice culture are: irrigated lowland, rainfed lowland, irrigated upland, seasonally flooded wetlands and tidal wetlands. On a global scale, rice grown in flood-prone and tidal wetlands, and under rainfed upland, irrigated lowland and irrigation conditions, constitutes 10 per cent, 10 per cent, 25 per cent and 55 per cent of the cultivated rice area, respectively. Irrigated rice, rainfed lowland rice, rainfed upland rice and rice from flood-prone areas account for 75 per cent, 17 per cent, 4 per cent and 4 per cent, respectively, of global rice production. For any given region or season, prevalent cropping systems cannot be considered ideal for optimal crop productivity. The sections that follow will examine, for each of the main rice ecosystems, their climatological requirements, the weather vagaries that impair operations, and the agronomic measures that have been established to cope with weather anomalies.

10.6.2.1.1 **Irrigated lowland rice ecosystem**

The coleoptile of the germinating rice seeds can elongate under anaerobic conditions (Apli and Beever, 1983) and rice can thrive under these conditions. Rice can, therefore, be raised with standing water over the soil. The system in which rice fields are banded to ensure ponding of irrigation water for most of the crop’s life, from sowing to a short time before harvest, is called the irrigated lowland rice ecosystem.

In this system in tropical Asia, an area equivalent to one tenth of the main field area is set apart as nursery. Seeds soaked in water for 24 to 36 hours are incubated for about 48 hours in a warm environment to facilitate germination, and the pre-germinated seeds are broadcast on the drained seedbeds of the nursery, which is kept wet for five days and gradually flooded thereafter. After a nursery time roughly equivalent to 3 and 2 weeks, for varieties with a duration of 4 to 4.5 months and 3 months, respectively, the seedlings are transplanted in the main field. Prior to transplanting, the soil in the main field is puddled, that is, ploughed, harrowed and finally levelled, with standing water in the field. Water from the main field is drained only when the crop is ready to be harvested.

The irrigated lowland rice cultivated in the United States and Brazil is quite different from that of Asia. In the United States, rice is grown as a single crop per year in three main areas: the semi-arid Sacramento Valley of California, with less than 50 mm of rainfall during the growing season; the humid subtropical areas of the Gulf Coast of Louisiana, Texas and Florida, with a seasonal rainfall range of 700–1 000 mm; and Grand Prairie and the Mississippi and Missouri river deltas. Dry seeding with a mechanized grain drill is the most common method of planting in the southern United States. In California and south-western Louisiana, pre-germinated seeds are seeded into standing water. In Brazil, the lowland irrigated rice is concentrated in the southern states of Rio Grande do Sul and Santa Catarina. In the former state, in about 80 per cent of the area, two years of rice are rotated with three years of pastures; only one crop per year is established, in which dry seed is broadcast or line-sown in dry soil. In Santa Catarina, irrigated rice areas are planted once a year using pre-germinated seed in puddled soil.

10.6.2.1.1.1 **Weather-related and other constraints and adaptive measures**

The availability of water to raise the requisite area of nurseries ahead of the normal dates of availability of surface irrigation is a major constraint in many areas. In places with adequate groundwater availability, community or individual nurseries known as reduced-area wet-bed nurseries are raised. In places where groundwater is rather scarce, modified mat nurseries are raised. In both methods seedlings are ready for transplantation within about two weeks of sowing, the area required for the nursery area is one per cent of the main field area, and high seed rates are used to ensure the adequate number of sturdy seedlings for transplanting in the main field.

Transplantation shock delays phenological development of the crop, especially tillering. Recovery from transplantation shock and potential yield increase and decrease, respectively, with an increase in the age of seedlings. Irrigated lowland rice requires enormous amounts of water for field preparation. Thus, to properly time the commencement of nurseries, a firm indication of the date of
availability of canal water for irrigation must be known in advance. The latter in turn calls for a quantitative and reliable forecast of rains in catchment areas of the irrigation systems about two weeks in advance. Quantitative rainfall forecasts with a lead time of 15 days are not currently available.

To overcome weather-related constraints, direct wet seeding of rice is being resorted to with increasing frequency. In this system of culture, after receipt of canal water, pre-germinated rice seeds of varieties with suitable characteristics for direct sowing (Yamauchi et al., 1993), namely good germination under anaerobic conditions with good initial seedling vigour, are broadcast or line-sown with drills in drained fields. Random broadcasting leads to great variations in seedling density. Row seeding of germinated seeds is costly but helps in maintaining optimum density of seedlings, controlling weeds and ensuring better crop management. After sowing, the field is intermittently wetted for a week and flooded thereafter. Provided that a good vigorous stand of seedlings is established and weeds are kept in check, wet seedlings have a higher yield potential than transplanted rice (De Datta and Herdt, 1983).

Storms traverse the deltaic rice belts, often leading to flooding and occasionally causing storm surges. Avoidance of cyclonic weather is desirable. The times, duration, regions and frequency of stormy weather vary among the coastal rice belts, however, and the agronomic strategies to deal with them also vary. For example, in India, the coastal areas adjoining the Bay of Bengal experience cyclones, while the coastal areas of the Arabian Sea are practically free from stormy weather. The cyclones of the Bay of Bengal move in a westerly direction, show a southward shift in their origin in the bay with the progress of the Indian summer monsoon, and occur over specific, short, one-month periods. In such a situation, a short-duration rice crop is harvested a little ahead of the cyclone season. Copious rains from cyclones are then used for puddling of soil for nurseries for a second crop and transplanting of the second crop is done so as to ensure that the crop is short during the cyclonic season. For such a crop, arrangements are made for draining away the excess rainwater from storms. In the Philippines, typhoons occur from June to October in the eastern and northern parts of the country at the rate of about 20 per year. Only one of the four main rice-climate belts is affected by typhoon weather. The subtropical rice-growing region in the United States, namely, the Gulf Coast of Louisiana, Texas and Florida, is subject to violent storms from June to November. Warnings of stormy weather, required to effectively cope with flooding of fields, are available and are quite accurate and timely.

### 10.6.2.1.2 System of rice intensification

Irrigated lowland rice requires an enormous amount of water for field preparation. In this system, loss of water through seepage can be reduced. Percolation loss through the soil is unavoidable and is independent of the season (Achar and Dastane, 1970), but it is influenced by soil type, depth of standing water and perimeter of the field area (Dastane et al., 1970). Percolating water from rice fields carries the risk of pollution of groundwater aquifers though the leaching of agrochemicals. Depending on soil types and cultural practices, the percolation and seepage losses are about 50 per cent of the consumptive (evapotranspiration) requirements of the crop. Thus, the water needs of puddled rice are two to three times those of an irrigated aerobic crop.

The system of rice intensification (SRI) was discovered following an accident and the observation in Madagascar in 1983 that transplanting rice seedlings of 8 to 15 days of age gave a very high number of tillers compared to the customary transplanting of seedlings of 30 to 35 days of age (Laulane, 1993). This discovery was followed up to formulate a set of practices that now constitute the SRI methodology (Satyanarayana et al., 2007). At present, even small farmers in more than 20 countries are using SRI.

In the SRI methodology, preparation of the main field is done in the same way as under the lowland irrigated ecosystem. The nurseries raised are similar to the reduced-area wet-bed or modified mat nurseries. Eight- to 12-day-old seedlings, with just two leaves and with seed, soil and roots intact, are removed by scooping and transplanted gently in a muddy field within 12 hours of removal from the nursery at a depth of 1 to 2 cm, singly in a square pattern of 25 cm × 25 cm, with the roots lying horizontally in the moist beds. Until the roots get established, a thin layer of water is let into the field at night and water is drained away in the morning. Afterwards the soil is kept moist but not saturated by irrigating the crop once every five to six days or by resorting to irrigation when surface cracks appear. A low level of water in the reproductive crop phase is not mandatory and alternate wetting and drying can be resorted to. Weeding, by rotary hoe, is done at 10-day intervals, starting from the tenth day after transplanting until the crop canopy closes. Weeds are returned to the soil to act as fertilizer and instead of chemical fertilizers, farmyard manure or compost is used.
The problems that arise in raising nurseries using the SRI method are the same as those encountered with the conventional method. The direct wet seeding of rice with pre-germinated seeds in moist soil has been suggested as an SRI procedure (Rao, 2004). SRI yields are dependent on strict adherence to geometry of planting and population density, however, and as these two features cannot be achieved by direct seeding, direct wet seeding is not advised (Satyanarayana, 2005). Beginning an SRI nursery at the same time that operations to prepare the main field are started will not depress yields as much as using the conventional method, however, because: SRI nurseries need only one third the nursery time that conventional nurseries require; minimization of transplantation shock in the SRI methodology further reduces the physiological age gap between conventional and SRI seedlings; planting young seedlings ensures preservation of tiller production potential of the seedlings; and an SRI crop matures 10 days earlier than a conventional crop.

Even when not exclusively used, SRI practices such as SRI irrigation with conventional planting or SRI planting with conventional irrigation, boost the yields of rice (Horie et al., 2005). From a review of water savings and yield increases in SRI rice compared with conventional methods in China and tropical Asian countries (Satyanarayana et al., 2007), one could surmise that with the same quantum of water as is being used in the conventional method, rice output can be doubled, trebled and quadrupled in areas with present yield levels of over 5 t/ha, 3–4 t/ha and 2 t/ha, respectively, with the aid of the SRI methodology.

10.6.2.1.2.1 Plausible reasons for yield increases and variations under SRI

From the limited experimental material available on rice and the influence of aerobic and anaerobic conditions on soil and plant processes in other crops, Satyanarayana (2005) has offered some explanations for the observed increases in rice production under SRI by comparison with flooded rice.

Young rice seedlings retain their potential for formation of tillers if they are transplanted before the start of the fourth phyllochron (Stoop et al., 1992), that is, before 15 days of age in tropical conditions. In each phyllochron one or more phytomers, namely, the set of tiller, leaf and root, are produced from the apical meristem; the number of tillers, leaves and roots will depend on the number of phyllochrons completed before flowering (Satyanarayana, 2005). This is especially true for SRI rice, less so for flooded rice. Even under SRI, however, the number of phyllochrons completed in the vegetative phase can differ with variety, season and location. Thus, weather factors may significantly account for areal variations noticed in tiller density of rice cultivars under SRI culture.

Wider spacing of plants and daily wetting and drying: (i) expose the soil for better absorption of solar radiation, oxygen and nitrogen; (ii) deny the ideal microclimate needed by many pests and diseases; (iii) contribute to a greater interception of the full intensity of sunlight by the crop canopy and hence to better photosynthesis; and (iv) lead to greater soil aeration. For its part, greater soil aeration results in better and firmer root growth and an increase in aerobic microbes that facilitate increased solubilization of phosphorus, mineralization of nitrogen, availability of main and trace elements from the entire soil column to the crop, and suppression of nematodes and rice diseases. Under flooded conditions, 30 to 40 per cent of the cortex around the central stele disintegrates to form aerenchyma cells (air pockets) that enable oxygen to diffuse to the roots. Thus, a great deal of energy is spent in the development of air pockets. Under non-saturated soil conditions, this energy is diverted to grain production.

10.6.2.1.2.2 Constraints in use of SRI

The use of SRI requires skilled labour for more days, though for fewer hours per day. As labour cannot be hired on an hourly basis, the labour cost becomes substantial. SRI seedlings are highly vulnerable to inundation in the first few weeks of growth. Lack of drainage facilities in areas where SRI is replacing conventional flooded rice is a handicap. Since current SRI rice areas have been subject to waterlogging for long periods, soil amelioration and detection and correction of deficiencies of micro- and trace elements, particularly iron, pose problems. Incorporation of weeds as the sole source of biomass addition is inadequate. The organic system of rice crop fertilization is considerably costlier than inorganic fertilization. The heavy incidence of insects such as mealy bugs, thrips and stem borers under SRI has been reported. The micro-levelling of fields that has been advocated as a measure to control thrips and mealy bugs is not seen as practicable.

10.6.2.1.3 Rainfed lowland rice ecosystem

Rainfall is the only water source for the rainfed lowland rice ecosystem. Rainfed lowland rice is raised in places where surface irrigation is not avail-
able and there is a risk of inundation of fields from rains for significant periods of time in the crop season. In this cultivation system, rice is grown in bunded fields with overflow arrangements to ensure that the depth of standing water remains less than 50 cm over a period of 10 consecutive days. The rainfed lowland system is characterized by uncertainty about the starting time of the crop season, and intermittent ponding, saturation, wetting and drying of the soil in a random manner. Methods for the establishment of crops are the same as in the irrigated lowland ecosystem. In the case of soils where rainwater tends to accumulate quickly on the soil surface, rainfed lowland rice may be established by direct dry seeding.

10.6.2.1.3.1 On-farm reservoirs

Due to rainfall vagaries, rice fields in the rainfed lowland system run the danger of drying up frequently during the active growth stage of the rice crop. The option of digging out a portion of the main rice field to collect surface runoff from rains, a method called on-farm reservoir (OFR), and using this storage to save the main rice field from drying out and to raise an aerobic crop after harvest of the rice crop, has been introduced and is in practice. The use of models for designing OFRs is of recent origin (Srivastava, 2001). For determining the fraction of field to be set aside for OFRs, it is necessary to know, for a given crop, when preparation of the main field for raising the crop will be started, as well as the temporal march of the quantum of rainfall deficiency by comparison with the crop’s water need, and surface runoff from rains. In this effort, the assessment of daily runoff for a large number of station-years by standard procedure (USDA, 1972) constitutes a daunting task.

10.6.2.1.3.2 Rainfall budgeting

The parameters required for design of an OFR can be assessed through a modification of the daily rainfall budgeting procedure of Pandey et al. (2005), keeping the following aspects in mind:

(a) The water need for land preparation (WNL), depending on soil type, will be 200 mm plus or minus 50 mm, while the need for raising the nursery will be 50 mm;

(b) The budgeting will involve two phases – the unsaturated phase before ponding of water becomes feasible and the saturated phase with standing water;

(c) The maximum moisture available for the crop will be between saturation moisture content and permanent wilting point;

(d) Rainfall for ponding will be available only after saturation of the root zone;

(e) Percolation (P) and seepage (S) will occur only with standing water on the field and will range from 2 to 4 mm per day, depending on soil types.

10.6.2.1.3.3 Methodology

The relevant methodology can be outlined as follows:

(a) Cumulate on a daily basis differences between rainfall (RR) and potential evaporation (PE). Take negative values as zero. Set the limiting value of such cumulations as equal to saturated soil moisture content (SSMC).

(b) Assign values in excess of SSMC as depths of water available for ponding (DW).

(c) The time when cumulated DW reaches the value of WNLP is the start of the saturated phase.

(d) In the saturated phase, starting with a given depth of water, add daily rainfall to depth of standing water and subtract the potential evapotranspiration (PET) seepage and percolation losses and assign excess values to runoff (RO).

(e) The time when such cumulations lead to nil depth of water is the time of onset of water deficiency and the water need will be equal to the desired depth of water level (D).

(f) Runoff collections in OFRs will also be subject to evaporation, percolation and seepage losses. Percolation and seepage can be prevented by lining the bottom and sides of an OFR with low-density polyethylene (LDPE) sheets.

In view of the plethora of terms and methodologies used in meteorological computation of peak crop water needs, FAO has prescribed a methodology to compute reference evapotranspiration \( \text{ET}_o \) as a standard datum. In the above example, PE will equal \( \text{ET}_o \), while PET for crops will be equal to \( K_c \cdot \text{ET}_o \), where \( K_c \) is a crop coefficient. Evaporation from pan evaporimeters, EP, is an easily available parameter that can be related to \( \text{ET}_o \). Venkataraman et al. (1984) have presented a methodology for computation of \( \text{ET}_o \) using available data on net radiation components and the variations in time and space of the ratio of \( \text{ET}_o/ \) EP. FAO (1998) gives procedures for calculating \( \text{ET}_o \) from EP recorded with different pans, their settings and surrounding environment, in combination with the values of \( K_c \) for peak water needs for various crops. The values for saturated soil moisture content, seepage, percolation and water needed for land preparation and optimal depth of standing water vary with soil types, but are readily available.
Applying the above methodology over a large number of years at a particular location will give, on a probability basis, the quantum of supplementary irrigation needed and the quantum of surface runoff that can be harvested. The two parameters can help in deciding the fraction of the main field that should be set aside for constructing the OFR.

10.6.2.1.3.4 Rice-cum-fish culture

Although FAO recognized the importance of rice-cum-fish culture as early as 1948, interest in this mode of farming was renewed only in the late 1970s (Ghosh and Saha, 1978). In India, where rice-cum-fish culture seems to have originated and which has the largest rice acreage, the percentage of rice area under rice-cum-fish culture is only 0.05 per cent, though the potential for this type of production is 45 per cent (Mohanty et al., 2002). In China, only 4 per cent of the rice area is under rice-cum-fish culture. Egypt, which has only 10 per cent of the area that India has under rice, has 75 per cent of the area under rice-cum-fish culture. Thailand has the highest area (3 million ha) and fraction of total area (32 per cent) under rice-cum-fish culture.

Irrigated lowland rice areas are suitable for rice-cum-fish culture. Fish culture requires a greater depth of standing water over the field than rice and will lead to a further reduction in water use efficiency. In deepwater rice areas and tidal rice wetlands, stocked fish may escape from the rice fields due to overflow of bunded fields by floodwaters. Thus, rainfall lowlands emerge as the only suitable system for rice-cum-fish culture.

When fish and rice are grown together, fish damage the rice crop and chemical control of biological setbacks to rice can harm fish. Again, the requirements of water depth, temperature, pH, oxygen and water turbidity for fish and rice for optimal performance are quite different. Also, water level in the fields cannot be allowed to fall below a specified minimum while fish stocks are present in the rice field. Thus, raising fish concurrently, but stocking them in OFRs, is called for. OFRs used as fish pens will require a higher depth of standing water. Therefore, a higher fraction of the main field has to be set apart for an OFR-cum-fish pen and this can be agroclimatically calculated (Bhatnagar et al., 1996). The fish catch from the fish pens will represent additional income for the farmer, however (Pandey et al., 2005), and will compensate for yield loss of rice from areas used for fish culture as well. Lining of the bed and sides of the OFR-cum-fish pen with LDPE sheets will be highly desirable.

10.6.2.1.4 Upland rainfed rice ecosystem

The upland rainfed rice ecosystem, in which the rice crop is raised in unbunded fields, is located in areas lying above the flood plain. A rainfall regime of 100 mm per month for four consecutive months is considered suitable for upland rainfed rice culture, which is mostly found in Asia, Africa and Latin America.

In upland rainfed culture, the crop is dry-seeded directly on ploughed land and the seeds are incorporated into the soil by ploughing or harrowing while the soil is still dry. Sometimes rice is dibbled, broadcast or row-sown in soil wetted by rains. In medium- and light-textured soil a dry nursery equivalent to 5 per cent of the main field area is raised. In this sector the seeds are sown dry and the soil is kept moistened; the seedlings are transplanted when rains start falling regularly.

Ideally, the completion of the vegetative phase of rice should coincide with the cessation of rains, with root-zone moisture at field capacity moisture status. The differences in duration among rice varieties are due to differences in duration of the vegetative phase. The reproductive and ripening phases are of 35 and 30 days, respectively, for most varieties. Since the evaporative power of air is 4.0 to 5.0 mm per day in the rainy season in the rice areas (WMO, 1967), the start of the cropping period for rainfed rice is the when rainfall begins and continues to exceed 30 mm per week; the vegetative period should end with the week in which rainfall drops below 20 mm. Therefore, the duration of the variety to be used is equal to the duration of the vegetative phase as delineated above, plus two months.

Maintenance of root-zone moisture of the rice crop is needed at saturation and not submergence (Venkataraman and Krishnan, 1992). In upland rainfed rice, this is not possible, as fields are not bunded. A budgeting of rainfall versus potential evapotranspiration of the rice crop, subject to the limiting plant-available soil moisture of the rice crop root zone, will give a measure of the climatological risks involved in raising rice as an upland rainfed crop at a given location.

10.6.2.1.5 Flood-prone rice ecosystem

There are two types of flood-prone areas: deep-water rice areas and tidal wetlands. The former are found in the lowland, deltaic areas of rivers where water accumulates for 30 days or more to depths of 0.5 to 3 m in the rainy season. Deep-water rice areas are common in South and South-East Asia and West Africa. In wetlands, soils remain flooded for several
weeks per year, often for more than 10 consecutive days, with medium (50 cm) to very deep (300 cm) flooding. Tidal wetlands are in coastal areas subject to risk of seawater intrusion as a result of storm surges. Tidal wetlands are more prevalent in Bangladesh and eastern India.

In deep-water rice culture, varieties known as floating rice are used. The seeds of such varieties are capable of germination even under 15 cm of water. Deep-water rice is directly dry-seeded but the seeds are not incorporated into the soil. The plants growing under non-flooded conditions can elongate their stems at a rate of 15 cm per day with a rise in water level up to 2 m in height. For this rate of elongation, however, the plants must be at least 6 weeks old. Deep-water rice can also survive submergence for 15 days.

10.6.2.1.6 Irrigated aerobic rice ecosystem

The irrigated aerobic rice ecosystem is a system of rice production that does not require puddling of soil and standing water in rice. Under aerobic conditions, various methods are adopted for supplying water for crop use, namely:

(a) The soil is ploughed dry and the field is surface-irrigated when the soil moisture in the root zone reaches a tension of –30 to –50 kilopascals;
(b) Alternate wetting and drying of the field is performed, in which the field is allowed to dry out for a few days after the standing water in the field disappears, before irrigation is initiated;
(c) Rice is raised in beds divided by furrows. Beds are initially ponded to keep out weeds. Later, a shallow depth of water is maintained in the furrows to ensure saturation moisture for rice;
(d) Rice is raised in beds initially wetted to saturation and water is later supplied to the root zone to replace the previous days’ loss by crop ET.

Non-flooded soil leads to a reduction in rice yields. Therefore, the main criterion in the above system is that, by comparison with flooded rice, any reduction in yield should be more than compensated by a savings in irrigation water. This will ensure that, with the same amount of water required for flooded rice, a larger surface can be covered under aerobic irrigated rice and a larger rice crop produced. Ideally, studies comparing water used in flooded rice versus aerobic irrigated rice exposed to the same weather should be done during the dry season. Papers detailing the water use of aerobic, irrigated rice in comparison to flooded rice in the dry season seem to be extremely limited (Atlin et al., 2006; Bouman et al., 2005; De Dios et al., 2000). Some interesting features that emerge from such studies are outlined below.

A 30 per cent reduction in yield in the dry season has been reported under aerobic conditions compared with flooded conditions (Bouman et al., 2005). Atlin et al. (2006), however, noted no differences in grain yields between flooded and non-flooded methods in the dry season. Bouman et al. (2005) reported that the savings in water used for aerobic irrigated rice vis-à-vis flooded rice are mostly due to savings in water needed for preparation and seepage and percolation and that reductions resulting from evaporation and transpiration are marginal. Water required for puddling of soil in flooded rice culture is a one-time requirement independent of the duration of crop field life and season. The percolation and seepage losses vary with the soil, but little with the season and range from 2 to 4 mm per day (Yoshida, 1981). The total quantum of seepage-cum-percolation losses is dependent on both soil type and crop field life. For a rice cultivar that is raised for the same length of time on the same soil under flooded and irrigated conditions, the quantum of water saved due to non-flooded irrigation will depend upon the quantum of water consumed by the flooded rice, which will be higher in a drier, hotter and brighter environment. Thus, differences in the quantum of water saved are to be expected in the range of 25 to 60 per cent in raising aerobic irrigated rice without a moisture stress, as a fraction of water used for flooded rice. The savings in irrigation water in aerobic rice culture will always be more than the reduction in yield in comparison with flooded rice and can be translated into a larger area under rice for the same quantum of water, especially in situations where the farmers do not have access to enough water to grow flooded lowland rice. Thus, from the standpoint of making efficient use of water in boosting rice production, the adoption of aerobic irrigated rice culture is called for.

It is also claimed that aerobic rice varieties, which are upland varieties distinguished by their indica germplasm, higher yield potential, better response to fertilizer, improved lodging resistance, higher harvest index, and tolerance to occasional flooding, can give as high a unit area yield as traditional varieties under flooded conditions, and can produce more rice per unit amount of water used. Their maturity is reported to be delayed by 10 days, however. Considerable experimentation needs to be directed at the development of varieties for aerobic irrigated culture and the optimal site-specific crop and water management practices for sustained production of aerobic rice under continuous cropping, before aerobic varieties are widely adopted for upland irrigation.
10.6.2.2 Influence of critical climate and weather variables on growth and yield

10.6.2.2.1 Rice growth phases

As the weather requirements for optimal development are growth-stage dependent, it is necessary to delineate the growth phases and growth stages of rice in order to address the weather relationships affecting this crop. The main growth phases of rice are the vegetative phase, from emergence to panicle initiation (PI); the reproductive phase, from PI to completion of flowering; and the ripening phase, from end of flowering to grain maturity. The vegetative phase in rice is held to consist of a basic vegetative or juvenile phase, and a photoperiod-sensitive phase from the end of the juvenile phase to PI. The photosensitive vegetative phase is of short duration and the additional time due to the photoperiod factor, if and when operative, will make little difference to the total thermal time requirements of a cultivar (Venkataraman, 2004). Thus, the vegetative phase of rice can be treated as a single entity.

For rice, considering the postulations of Tanaka et al. (1964), Robertson and De Weille (1973), and Counce et al. (2000), the following growth stages can be delineated:

(a) Vegetative phase, consisting of the seedling stage, from primary leaf emergence to fifth leaf stage; transplantation stage, from fifth leaf to recovery from transplantation; tillering stage, from tiller initiation to maximum tillering; and stem elongation stage;

(b) Reproductive phase, consisting of the panicle initiation, booting (appearance of flag leaf), heading (exsertion of 50 per cent of the panicles), and flowering (opening and closing of spikelets) stages;

(c) Ripening phase, consisting of milk grain, dough grain and mature grain stages.

10.6.2.2.2 Temperature

10.6.2.2.2.1 Critical temperatures for rice growth stages

For delineating specific time periods suitable for maximal production of rice at a given location, it is necessary to know the cardinal (high, low and optimal) temperature requirements of various rice growth stages (Table 10.6.2). From the literature cited by Yoshida (1977), WMO (1983) and Venkataraman (1987), the low, high and optimal temperature requirements for important rice growth stages are given below.

The japonica cultivars of rice can tolerate temperatures 5°C lower than those of indica varieties, while their maximal values will be 5°C lower than those of indica varieties. The optimal temperatures will be the same for both japonica and indica varieties, however.

10.6.2.2.2.2 Duration of vegetative phase

The differences in duration of rice cultivars are due to differences in duration of their vegetative phase (Oldeman et al., 1987). In the phenology component of the ORYZA and CERES-rice models, a base of 8°C and 9°C mean air temperature is used, respectively, for computing thermal-time accumulations in rice crop phases. The above models have been reported to account for vegetative phase durations at individual locations. The CERES-rice model has been found to be

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superior to the ORYZA model and accurately accounts for variations in the duration of the vegetative phase ranging from 37 to 85 days, which arise from variations in varieties and locations (Mall and Aggarwal, 2002). The duration of the vegetative phase decreases with increases in temperature up to 33°C; a temperature rise above 33°C has no further decreasing effect (Alocilja and Ritchie, 1991).

The work of Reddy et al. (2004) indicates that vegetative phase durations expressed as growing degree-days above a base mean temperature of 10°C will be conservative across seasons. The degree-day requirements for completion of the vegetative phase can be expected to vary among cultivars. Thus, even limited and random phenological observations on growing degree-days in the vegetative phase of rice recorded on a few typical short- and long-duration cultivars, at a few locations and/or seasons, can assist in gauging the vegetative duration of different cultivars in various regions and seasons through temperature links.

10.6.2.2.2.3 Tillering

The number of tillers per unit area has a great bearing on rice yields (Yoshida and Parao, 1976). The duration of the tillering phase is influenced by temperature (Lalitha et al., 1999). At 23°C the duration is 8 weeks; it is only 5 weeks at a temperature of 27°C. The number of tillers per unit area is also influenced by temperature and shows a sharp rise at a temperature of 27°C (Lalitha et al., 2000). The contention (Owen, 1972) that the lower rate of production of tillers at low temperatures will be more than compensated by the increased duration of tillering is not valid (Reddy et al., 2007). Cumulated leaf area in the vegetative phase determines the quantum of intercepted photosynthetically active radiation, which is a yield-determining factor. The optimal leaf area index for photosynthesis in rice is 4.0 (Murata, 1967). The time required to reach an LAI of 4.0 from planting depends on tiller population and rate of tiller production, both of which are influenced by temperature. Again, the time between attainment of an LAI of 4.0 and the end of the vegetative phase becomes crucial and is dependent upon temperature.

10.6.2.2.4 Application of nitrogenous fertilizers

At temperatures optimal for tillering, leaf emergence will not be significantly affected, but elongation will be slower. Slower elongation will have little influence on cumulated leaf area, however. The need to ensure adequate and timely supply of nitrogen to the crop for quick and proper leaf growth becomes important. The optimum time for application of nitrogenous fertilizers in rice is when the average internodal length is 6 mm; applications at internodal length up to 12 mm have little effect on yield. As reported in WMO (1974), the 12 mm internodal length corresponded to a value of 200 effective heat units, or EHU, accumulated with lower and upper limits of 21°C and 31°C, respectively. Thus, if the daily temperature is 20°C, the EHU will be zero. Similarly, if the daily mean temperature is 33°C, the EHU will be only 31. Thus, the concept of EHU provides an agrometeorological tool for fertilizer applications.

10.6.2.2.5 Net biomass accumulation

The dry matter accumulated at heading has a significant influence on the grain yield of rice (Yogeswara Rao et al., 1999). Most of the dry matter in rice grain comes from post-floral photosynthesis. Part of the photosynthate is used as growth respiration, namely, in the formation of plant tissue, and the rest is used as maintenance respiration in the upkeep of existing tissues. Maintenance respiration is a function of both temperature and net biomass. In rice, maintenance respiration is 10 per cent of available photosynthates at 25°C (Mall and Aggarwall, 2002) with a Q10 of 2.0 (Penning de Vries et al., 1989). Thus, temperature plays a major role in the creation of photosynthetic capacity in the vegetative phase and in the extent of utilization of the photosynthetic opportunity in the reproductive phase.

10.6.2.2.6 Reproductive phase

Work on the influence of temperature on growth stages and crop attributes in the reproductive phase (Best, 1959; Chang and Oka, 1976; Matsuo et al., 1995; Nishiyama, 1984, 1985; Yoshida, 1981) shows that non-optimal, low temperatures below 15°C for japonica varieties and below 20°C for indica varieties occurring during panicle initiation lead to a reduction in the number of florets per panicle and to the degeneration of panicle tips. After the formation of young panicles, they reduce the size of panicles; during booting they cause high sterility of spikelets; and in the booting and heading stages they delay heading, reduce the number and growth of spikelets, and lead to incomplete panicle exsertion. In the flowering stage they delay flowering and lead to non-flowering of lower spikelets and incomplete fertilization; during anthesis, they reduce pollen maturity and floret fertility owing to inhibition of anther dehiscence (Nishiyama, 1984).
10.6.2.2.7 Ripening phase

From international experiments on rice covering many varieties, locations and seasons from 10° N to 20° N, Oldeman et al. (1987) found that the duration of the ripening phase was conservative and was characterized by a growing degree-day of 825 accumulated over a base temperature of 0°C. The work of Reddy et al. (2004) shows that despite temperatures in the ripening phase varying from 24°C in the rainy season to 31°C, the duration of the phase was constant at about 29 days across varieties and seasons. Optimum night temperature for this phase is thought to be 23°C (Ebata and Nagata, 1967) and minimum temperature in the 30-day period following flowering is viewed as an important yield-determining factor (Seshu and Caddy, 1984).

10.6.2.2.3 Solar radiation

10.6.2.2.3.1 Vegetative phase

The dry matter accumulated at heading, which has a significant influence on the grain yield of rice (Yogeswara Rao et al., 1999), is directly proportional to the quantum of intercepted photosynthetically active radiation (PAR). Now PAR is 45 per cent of solar radiation (Monteith, 1965). Thus, contrary to the popular notion, solar radiation in the vegetative phase is very important and the aim should be to maximize intercepted solar radiation in this phase.

10.6.2.2.3.2 Reproductive and ripening phases

A rise in radiation up to 500 calories/cm²/day increases the number of spikelets (Yoshida and Parao, 1976), which is an important indicator of dry weight at heading (Kudo, 1975). Solar radiation in the range of 300 to 600 calories/cm²/day in the post-flowering period was positively related to the number of filled grains per panicle, ranging from 50 to 180 (Oldeman et al., 1987). Solar radiation in the ripening phase influences both the percentage of well-filled grains and weight per grain. For equivalent yields, the radiation requirement in the ripening phase is lower than that of the reproductive phase because: (i) the amount of dry matter produced in the ripening phase is less than that at the start of the ripening phase; (ii) a substantial portion of photosynthates formed in the reproductive phase is used in grain yield (Yamada, 1963); and (iii) when photosynthesis gets restricted in the ripening phase, about 70 per cent of the stored carbohydrates at the start of the phase are translocated to grain (Yoshida, 1972). A cumulative solar radiation of 14 000 calories/cm² in the ripening phase (Moomaw and Vergara, 1964), preceded by 6 to 7 hours of bright sunshine per day in the reproductive phase (Sato, 1956), is thought to be optimum for rice grain yield.

10.6.2.2.4 Rainfall

The type of rains needed for puddling of soil can come only from inland movement of depressions or with heavy rainfall-producing systems. In the absence of marine formations and/or inland movement of depressions or heavy rainfall systems, the area under puddled rice goes down. Since the soil surface of a rice field has standing water or is kept saturated, the consumptive-use (evapotranspiration) requirement of an established rice crop will be equal to the evaporative power of air (EPA). The value of EPA in the rainy season is 4.5 mm per day (WMO, 1967). Considering the percolation and consumptive-use needs of puddled rice, an amount of 50 mm of rain per week would be needed by an established, rainfed puddled rice crop. The ideal rainfall interval will be the saturated soil moisture content of the crop root zone divided by 50. In view of the nature of the climatology of the temporal march of short-period rainfall, collection of runoff from rains in OFRs for puddled rice becomes mandatory to deal with periods of moisture stress for the crop. In this sense, it is not the requirement of rainfall, but rather the management of rainfall that is of utmost importance in rainfed rice culture.

10.6.2.2.5 Water requirement

The physiological make-up of a crop plays a vital role in the water uptake of the crop during maturity. Limited data recorded with a volumetric lysimeter system show that varietal variations in the physiological control of water needs are likely (Venkataraman, 1982). As the soil is kept moist until the crop is harvested, however, there is no reduction in the water needs of rice during the maturity period. Thus, the water requirement of irrigated lowland rice will be the same as the rainfall requirement of rainfed lowland rice exposed to the same weather. Limited but critical field trials show that, under the aerobic irrigated system, savings in water will come from water for field preparation and percolation losses; these savings can range from 30 to 100 per cent.

10.6.2.2.5.1 Water-sensitive crop phases

For organizing water-saving measures, it is necessary to know the phases when rice is sensitive to water stress and to submergence. Moisture stress in the vegetative stage reduces plant height, tiller number
and leaf area, but the crop can recover without much loss in yield if adequate moisture is restored before flowering. Rice is most sensitive to moisture stress in the reduction division stage (panicle initiation through flowering) that leads to high spikelet sterility. The yield reduction due to submergence depends on the duration of submergence, the crop stage during submergence and the muddiness of the water. Reduction in yield is two times greater under muddy water compared with clear water. The panicle formation stage and ripening phase are the most and least vulnerable to submergence, respectively.

10.6.2.2.6 Wind

Only very low wind speeds are required for replenishment of the CO$_2$ supply to the rice plant through turbulence in the crop canopy. Strong winds cause too much fluttering and waving of the crop canopy, which interferes with the ascent of sap and hence affects mineral nutrition. This motion also reduces the formation of photosynthates and leads to poorer retention of assimilation product in ears. Dry winds desiccate ovaries and increase sterility, and they blow the pollen off stigmas, especially on plants with feathery stigma or with a long gap between the opening and closing of the lemma and palea (Saran et al., 1972).

10.6.2.2.7 Relative humidity

Relative humidity (RH) below 40 per cent inhibits flowering, which is best when RH is 70 to 80 per cent (Angladette, 1966). Relative humidity of even 60 per cent leads to faster senescence of leaves (Hirai et al., 1984). Higher RH increases stomatal aperture and leads to greater photosynthesis irrespective of the solar radiation regime (Hirai et al., 1984). Thus in the dry weather season, growing rice in puddled conditions would appear necessary to ensure a requisite RH regime. The influence of RH on rice crops has not been widely studied and this topic needs to be addressed.

10.6.3 Other background information on rice

10.6.3.1 Climatic variability

FAO (1992) uses the term “climate fertility” to stress the direct link between agricultural production potential and climate. Rainfall, temperature and solar radiation, directly or indirectly and singly or in combination, affect the growth, development and yield of rice cultivars. Climatic variability in the above parameters is the major reason for differences in the variations in the yield potential of rice cultivars in various regions and seasons. Within the above broad picture, several types of climatic variabilities occur, and they need to be recognized for microscale planning in rice agronomy.

The first type of climatic variability is the one associated with regular weather systems that traverse specific regions in specified periods, such as the monsoons. Even when seasonal total rainfall or seasonal mean temperatures are considered, despite the annual fluctuations, an increasing or decreasing tendency over a period of years is often discernible. This gives rise to the concept of increasing or decreasing epochs of a weather parameter and constitutes the second type of variability. The third type of variability is associated with non-permanent systems, such as El Niño or La Niña, that have varying return periods, times and duration of occurrence, and interact with, add to and/or influence the regular systems so as to reinforce or mitigate their variability. For example, the tendency for drought to occur during the Indian summer monsoon in El Niño years practically disappeared during periods of above-normal rainfall (Kripalani and Kulkarni, 1997). The fourth type of variability is caused by differences in the coefficient of variation among the weather parameters. As an example, rainfall and the evaporative power of air are, respectively, the most and least variable in time and space. Climatic features over short periods of time, such as a week or a dekad (10 days), have to be considered for crop planning that is suited to the local climate. The in situ interannual variations over short periods constitute the fifth kind of variability. The above types of climatic variabilities lead to real and seasonal variations in climatic fertility for the production of rice.

10.6.3.2 Climate change

Puddled rice culture leads to anaerobic decomposition of organic matter and to the production of methane, a key constituent of greenhouse gases responsible for global warming and climate change. Under a wet undisturbed soil, the methane from soil does not escape into the air. Cultural practices associated with irrigated lowland rice account for 30 per cent of the soil methane released into the air, while aerenchyma cells of the rice plant provide the conduit for 70 per cent of the methane released into the air. Methane constitutes barely 2 parts per million (ppm) of air, compared with 350 ppm of CO$_2$. A methane molecule is 30 times more efficient in trapping heat compared with a molecule of CO$_2$, however. It has been reported (Reddy et al., 2005)
that higher biomass production of rice and higher incorporation of organic matter in puddled fields increase methane emissions. Lowland rice thus constitutes a significant source of atmospheric methane (Cicerone et al., 1983).

Climate change is expected to result in increases in rainfall variability, mean and night-time air temperatures, concentration of carbon dioxide and cloudiness – all of which will adversely affect growth, development and yield of rice (Peng et al., 1995; Matthews et al., 1996). The magnitude of increases in the above factors forecast for the worst climate change scenario can be seen even now, both intra-seasonally and inter-seasonally. In real time, though, aberrations in any weather parameter are limited to short durations and the effects of one period of abnormal weather are often offset by another period of an opposing trend – as for rainfall and temperature. Climate change, however, is a unidirectional perturbation that is superimposed on climatic variabilities.

10.6.3.2.1 Impact assessment

There is diversity of opinion on the expected rate of increase in climate change parameters. The parameters change in an interdependent manner. For example, an increase in CO$_2$ concentration will be accompanied by a rise in temperature and increased cloudiness. Ambient weather conditions influence the degree of responses of a given crop to a given change of a given parameter. Therefore, in assessing the impact of climate change on rice, it is necessary to: (i) carry out assessments for typical rice areas and seasons; (ii) work in terms of realistic, optimistic and pessimistic future climatic scenarios by assigning to each of the above climatic scenarios class-appropriate and specified increases or decreases of relevant parameters; and (iii) adopt a holistic approach involving assessment of an increase or decrease in rice yields due to the specified changes in yield-determining parameters. These steps will help assess the net change in rice yield in each scenario class for various areas and seasons of rice culture (Venkataraman, 2004).

The dynamic crop weather models, like CERES-rice and ORYZA, use inputs derived from field and laboratory studies to simulate growth, development, production of net biomass and partitioning of net biomass to rice grain yield. They are useful for assessing relative changes in yield of a rice cultivar due to climate change. Many impact assessment studies using the models are deficient in one or more aspects of the requisite methodology, however.

10.6.3.2.2 Salient features for rice

The temperature increase linked to global warming would be more pronounced in night-time temperatures (Karl et al., 1991), leading to higher night minima and a decline in the diurnal temperature range (DTR), which is the daily range in temperature expressed as a percentage fraction of the maximum temperature. Rice is sensitive to both minimum temperature (Seshu and Caddy, 1984; Lal et al., 1998) and DTR (Lal et al., 1998). Unlike for other crops, elevated CO$_2$ has little effect on transpiration of rice and the effects of moisture stress on rice will not be mitigated under an elevated CO$_2$ regime. Reduction in solar radiation will lead to an equivalent reduction in rice yields (Ritchie et al., 1987; Hundal and Kaur, 1996; Yogeswara Rao et al., 1999). There is little chance that rice will become CO$_2$-saturated by the middle of this century (Sinha, 1993; Baker et al., 1990). Maintenance respiration can range from 4 to 16 per cent over the temperature range of 15°C to 35°C (Mall and Aggarwal, 2002; Penning de Vries et al., 1989).

10.6.3.2.3 Some observed features

Some investigations indicate that the rice yield can either increase or decrease under certain climate change scenarios and in certain regions and cultivars. Long-term field experiments in Japan have shown a decline in rice yields because of the increase in spikelet sterility due to higher temperatures (Horie et al., 1996). Historical trends and long-term fertility experiments show a modest decline in rice yields in many districts of north-west India (Aggarwal et al., 2000) and the Indo-Gangetic Plains of India (Swarup et al., 1998). Simulation studies help ascribe the above decline to rising temperatures (Matthews et al., 1996; Aggarwal, 2003). Even given an optimistic future climate scenario, a decrease in rice yields in all parts of the rice belt and in all seasons is considered to be likely in India (Venkataraman, 2004).

A 10 per cent increase in rice yields is indicated with warming of 1°C plus 100 mm of rain in southern China (Zhang, 1989). The increase is attributable to the higher rainfall, however. With a CO$_2$ level of 460 ppm and a temperature increase of 1°C to 1.5°C, rice yields are set to increase by 2 to 5 per cent in India (Rathore et al., 2001). An increase of 4 per cent has been indicated for irrigated rice yields in north-west India due to climate change (Lal et al., 1998). An increase in rice yields in all regions of India has been projected, both under optimistic and pessimistic scenarios of climate change, leading to a levelling out of
differences in regional predicted rice yields (Aggarwal and Mall, 2002).

10.6.3.2.4 Reasons for discrepancies

The diverse results mentioned can be explained by the ecophysiology of rice. The effect of any weather aberration on the rice crop depends on the growth stage of the rice at the time of the event. For example, high temperatures after heading lead to a reduction in grain yield (Tashiro and Wardlaw, 1991) and the decrease in spikelet fertility owing to high temperatures is not ameliorated by the associated increase in CO$_2$ (Allen et al., 1995). In East Java, Indonesia, high rice yields are obtained in the wet season due to a shorter grain-filling period resulting from high temperatures (Daradjat and Fagi, 1991). The ambient conditions during which the weather aberration occurs determine the response of rice. For example, while mean temperatures above 33°C do not lead to any further reduction in the vegetative or reproductive phases (Alocilja and Ritchie, 1991), the duration of grain filling decreases with an increase in temperature beyond 33°C. The rice crop can use the higher amounts of CO$_2$ associated with temperatures above 33°C. Thus, given the envisaged climate change, the southern and western regions of India that currently have lower temperatures are likely to have increases in rice yields that are smaller than those in the northern and eastern regions of the country (Aggarwal and Mall, 2002).

Crop-weather simulation models show that the level of CO$_2$ enrichment required to offset the influence of the rise in temperatures depends on the level of CO$_2$, and the rise in temperature that can nullify the effects of CO$_2$ enrichment depends on the level of temperature increase (Crisanto and Leandro, 1994; Hundal and Kaur, 1996; Mall and Aggarwal, 2002). Therefore, whether an increase or decrease in rice yields will result from any analysis depends on the level of the changes in weather parameters assumed, often arbitrarily, in the climate change model.

10.6.3.2.5 Extreme weather events

Rice is the only crop that can be grown in tracts subject to storms and floods. Studies (IPCC, 2007) indicate that an increase in the frequency and intensity of extreme weather events, such as El Niño, La Niña, floods, droughts, cyclones, typhoons, heatwaves, frosts and high winds, will be a feature of the climate change scenario. In the Philippines, the declines in production and yield are seen to coincide with the occurrence of El Niño events (Philippines Research Institute and Bureau of Agricultural Statistics, 2000). The lessening of the return periods of El Niño and La Niña and the recent occurrence of typhoons in the normally typhoon-free months of November/December in the Philippines is a cause for concern, as November and December are months when the rice crop is due for harvest and when the second crop is due to be planted (Lansigan, 2005). In India, the largely reduced formation of depressions in the Bay of Bengal and/or their subsequent lack of inland movement in recent years are affecting the acreage of puddled rice in some major rice-bowl areas.

Assessment of yield losses of rice under field conditions due to natural calamities is difficult because the quantum of reduction in yield is critically dependent on the stage of the crop’s development during which the calamities occur. For example, even a temporary moisture stress for a week centred around the time of heading of the crop can reduce crop yields by 60 to 65 per cent due to a sharp decline in spikelet fertility and slowing down of peduncle elongation (Liu et al., 1978). Direct-sown rice is less prone to drought than a transplanted crop. Droughts are more harmful than flooding in reducing yields of rice. Between 1968 and 1990 in the Philippines, droughts, floods and tropical cyclones, and pests and diseases were seen to account for 50 per cent, 40 per cent and 10 per cent of the total rice losses, respectively (Philippines Research Institute and Bureau of Agricultural Statistics, 2000; Lansigan et al., 2000).

10.6.3.2.6 Regional variations in actual and potential productivity

The FAO Expert Consultation on Yield Gap and Productivity Decline in Rice (FAO, 2004) has assessed the actual farm yield, potential yield and yield gap of irrigated rice in various countries. These are illustrated in Table 10.6.3.

Since the gap figures relate to irrigated rice, moisture stress as a yield-influencing factor can be ruled out. The potential yield is that obtained at experimental stations with no physical, biological or economic constraints and with best management practices for a given time and given ecology. The actual yield is the yield on an average farmer’s field given the same target area, time and ecology of the research station.

Table 10.6.3 shows that the yield gaps range from 10 to 60 per cent. Except in the Republic of Korea, the yield gaps between the actual and the potential in various rice regions range from 2.0 to 3.0 t/ha. Yields on farmers’ fields under the system of rice
intensification are considerably higher than those of rice grown conventionally at nearby research stations. SRI can easily reduce the yield gap. The effects of climatic variability on the production potential of SRI rice have been limited, however. The differences in potential yield among countries can be ascribed to differences in the climatic regimes of the cropping period. Higher yields per unit area are often attained due to a longer field occupancy by rice, however. For unit areas with lower yields, more time is available to grow a second crop, subject to the availability of water. Thus for meaningful comparisons of rice crop productivity, values would be required for yield per day per unit area and net profit per year per unit area.

10.6.4 Management aspects of rice in various environments

Rice is grown in diverse hydrologic environments with different cultural and crop management practices in each of these environments. Management of the rainfed crop restricts the scope of rice management. Under irrigation, the scope for the management of crops to improve unit area and gross yields is better. Cultural practices and features having a bearing on crop production within irrigation systems are linked to major weather features and climatic factors, namely, rainfall, temperature and solar radiation.

The time and manner of the onset of rains and the seasonal rains in the catchment areas of the source of the irrigation system determine, respectively, the time of land preparation for the first rice crop and the quantum of water available for irrigation. Solar radiation and temperature, as important constituents of the EPA, determine the command area that can be irrigated with water available for irrigation and optimal irrigation scheduling for crops in the crop season. The very high water needs for land preparation and meeting of percolation losses give little scope for adopting a seasonally varied command area for rice. The cropping calendar for the sequencing of rice and its rotational crops, and the duration of growth periods of these crops, vary from place to place as a result of variations in the phasic weather requirements of crops, the temporal march of radiation and temperature regimes, and the need to ensure that maturity periods of crops are sunny but not warm. Cropping intensity is the number of crops, including rice and its rotational crops, that can be raised in a year at a given place. The vegetative duration of rice, which determines the rice cropping period and the life duration of rotational crops of rice, is governed by the temporal march of the temperature regime. Fertilizer applications are timed as per phenological crop stages, which are influenced by temperature. Solar radiation and temperature are important for harvesting and crop processing, since sunny and warm weather is required in the pre- and post-harvest periods. These factors are tabulated schematically in Table 10.6.4 according to Bhuiyan and Galang, (1987).

10.6.4.1 Adaptive, protective and improvement measures

Adaptation of rice production systems to weather abnormalities and climate is an integral component of a balanced strategy to deal with climate variability. It is a measure of the degree to which adjustments to climate variability are possible in practices, processes or structures of systems. Adaptations are mostly agronomic. Protection measures relate to avoidance

<table>
<thead>
<tr>
<th>Country</th>
<th>Actual</th>
<th>Potential</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>India (northern)</td>
<td>4.0</td>
<td>6.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>7.0</td>
<td>7.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Philippines</td>
<td>5.5</td>
<td>7.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Viet Nam</td>
<td>6.5</td>
<td>8.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Egypt</td>
<td>8.5</td>
<td>10.4</td>
<td>1.9</td>
</tr>
<tr>
<td>Madagascar</td>
<td>4.1</td>
<td>6.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Italy</td>
<td>6.0</td>
<td>9.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Brazil</td>
<td>5.5</td>
<td>8.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>
of unfavourable climatic features and mitigation of hazardous weather effects. Improvement measures relate to desirable future developments.

10.6.4.1.1 Agronomic adaptation, commencement of cropping

Rainfall vagaries result in uncertainty in starting the rice crop, in both irrigated and rainfed agriculture. Raising nurseries and transplanting seedlings with a view to preserving the physiological age of the crop are attempts to overcome this obstacle. The reduced-area wet-bed nursery and mat nursery are adaptations to overcome water constraints. For irrigated rice, low temperatures of less than 15°C prevent raising nurseries in high latitudes. Uncertainty in the use of young seedlings for transplanting is overcome by direct seeding. The inability of dry rice seeds to germinate under flooding is overcome by wet seeding with pre-germinated seeds of varieties suitable for direct seeding under anaerobic conditions.

10.6.4.1.2 Choice of cultivars

The combined duration of the reproductive and ripening phases is 55 days, plus or minus 5 days. The optimum life duration for rice is 135 days, plus or minus 5 days (Moomaw and Vergara, 1964; Tanaka, 1964). Therefore, the optimal duration of the vegetative phase is 80 days. The reproductive and ripening phases must have about 8 hours of bright sunshine with mean temperatures not exceeding 30°C. Agroclimatic analysis can help delineate the best possible growing period for irrigated rice and thus identify cultivars that would perform optimally in a particular region and season given an early, normal or late start of the season.

The optimal duration for rainfed rice is very often not achievable as rice requires bright sunny weather during the ripening phase, and the crop must enter the ripening phase when rains cease, preferably with good root-zone moisture storage or with sufficient water available in the OFRs. This calls for the use of photosensitive varieties. Under lowland rainfed culture, delays in transplanting of photoperiod-sensitive varieties due to rainfall hold-ups have no significant effect on grain yield. It is agroclimatically possible to determine for any given location the time of commencement of the type of rains that will enable start of the lowland rice, and the time of cessation of significant rains. The former will derive the last possible date up to which transplanting/seedling of rice can be delayed without a reduction in yield potential, while the latter will provide the photoperiod regime for commencement of flowering and help in the choice of cultivars with appropriate photoperiod requirements for flowering.

10.6.4.1.3 Optimization of population density

The time from panicle initiation to about 10 days before maturity is the most critical period of solar energy requirement of the rice crop (Stansel, 1975; Stansel et al., 1965), when temperatures strongly interact with sunlight. Grain yield of rice is highly associated with dry matter at heading (Yogeswara Rao et al., 1999) and the increase in dry matter from the early start of panicle initiation to harvest (De Datta et al., 1999).

Table 10.6.4. Cultural practices for irrigated rice that are linked to major climatic factors

<table>
<thead>
<tr>
<th>Cultural practices for rice or related activities within irrigation systems</th>
<th>Climatic factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rainfall</td>
</tr>
<tr>
<td>Land preparation and crop establishment</td>
<td>•</td>
</tr>
<tr>
<td>Available water at irrigation system source</td>
<td>•</td>
</tr>
<tr>
<td>Command area</td>
<td>•</td>
</tr>
<tr>
<td>Cropping calendar</td>
<td>•</td>
</tr>
<tr>
<td>Cropping intensity</td>
<td>•</td>
</tr>
<tr>
<td>Crop management</td>
<td>•</td>
</tr>
<tr>
<td>Field water management</td>
<td>•</td>
</tr>
<tr>
<td>Fertilizer use and management</td>
<td>•</td>
</tr>
<tr>
<td>Irrigation delivery schedule</td>
<td>•</td>
</tr>
<tr>
<td>Harvesting and crop processing</td>
<td>•</td>
</tr>
</tbody>
</table>
10.6.4.2 Protection measures

10.6.4.2.1 Floods and droughts

Growing of puddled rice with standing water is in itself considered a bulwark against flooding. In rainfed lowland rice, risks due to flooding can be minimized by effective techniques for drainage of excess water in the field, such as openings in the field bunds at a level corresponding to the desired depth of standing water in the field, in tune with local aspects of plant and water management under excess moisture. This arrangement will result in a large quantum of rainfall becoming ineffective, however. Collection of runoff from rains in OFRs and introduction of water-saving techniques (Lansigan, 2005) are adaptive measures to mitigate drought situations caused by rainfall anomalies and to improve water use efficiency. The OFR system also provides an effective means of combating floods.

10.6.4.2.2 High winds

Strong winds lead to poorer mineral nutrition of the crop and enhanced spread of many diseases of rice. Establishment of windbreaks in strategic areas can help reduce wind damage in rice. For this action, information on prevailing wind direction in various months needs to be known, as windbreaks have to be erected perpendicular to prevailing wind direction. “Windroses” giving climatic information on a monthly basis regarding the frequency of occurrence of winds from eight cardinal directions and frequencies of occurrence of specified wind-speed classes in each direction are widely available and can be used for proper orientation and structuring of windbreaks.

10.6.4.2.3 Pests and diseases

During night hours, owing to back radiation, the rice canopy can cool to a value below the minimum temperature at screen level. When relative humidity is high, 75 per cent or more, winds are light or absent and the crop cools to a temperature below the dewpoint. Dew forms and wets the leaves. The times of onset and evaporation of foliar dew are called leaf wetness duration, which has a vital bearing on incidence of diseases. Leaf wetness duration can be measured by instruments (WMO, 1963; Lomas and Shashqua, 1970; Monteith, 1972). The procedure suggested for computation of leaf wetness duration by Matra et al. (2005) is not practicable for real-time use. The extent to which crop minimum temperatures drop below the screen level minimum varies with seasons and places. Data on depression of crop minimum below the screen minimum are available for many areas and seasons and can be used for extrapolation. The hourly distribution of temperatures can also be calculated from maximum and minimum temperatures (Venkataraman, 2002). Therefore, data on maximum, minimum, dewpoint and depression of crop minimum below screen minimum can be used climatologically to avoid disease incidence through crop planning and operationally to ensure effective control operations.

Rice is susceptible to a given pest or disease at a certain growth stage only. The pest or disease organism does damage at a certain development stage only. The predisposing weather conditions for incidence and spread of many important pests and diseases of rice are also available (Venkataraman and Krishnan, 1992). Such information can be used to agro climatically demarcate susceptible areas and periods for many major pests and diseases of rice. Along with the phenometeorological relationships of rice, this information can be used to avoid pests and diseases through a proper choice of sowing date or variety, or both.

10.6.4.2.4 Temperatures

Cold temperatures can arise from advection or local radiational cooling with a standing rice crop. Temperatures below 20°C and above 35°C for indica varieties and below 15°C and above 30°C for japonica varieties are potentially harmful. The extent of damage depends on crop growth stage, variety, temperature duration, diurnal range and physiological status of the plant. Cool weather
hazards to rice are often encountered in high-latitude regions. Low temperature incidence in hilly areas in the tropics and subtropics is a critical factor in rice production. Some types of cool weather damage to plants in typical growth stages of rice are indicated in Table 10.6.5.

In northern Japan, to overcome delays in the start of rice nurseries due to chilly simmers, the nursery beds are covered with oil paper or vinyl films and the nurseries are drained and reflooded frequently to maintain equable warm day and night temperatures (Matsuo, 1954). The protected seedbed method helps in extending the rice season from early spring to late autumn (Inoue et al., 1965). In northern China, seedlings are raised in plastic-protected nurseries when the air temperature is around 10°C, and transplanted to the main field when the temperature rises to 20°C. In the Kathmandu Valley of Nepal, seedlings are raised in unprotected nurseries when the temperature is about 20°C, transplanted to the main field, and harvested before the temperature falls to 13°C (Yoshida, 1978) and causes high sterility of spikelets. Similar approaches have been reported for some areas of Japan (WMO, 1975). The following measures (Barfield and Gerber, 1979), singly or in combination, can be used to cope with risks to rice on account of cold weather: heating or mixing of the air layers in the crop canopy, sprinkler or flood irrigation, artificial fogging and insulation with suitable material.

Usually, heatwave conditions arise from advection associated with en masse movements of warm weather systems. Local heating of the surface leading to high air temperatures occurs in summer and generally after the harvest of the rice crop. High temperatures in the vegetative phase reduce the duration of tillering but enhance tiller production, with the result that the total number of tillers is hardly affected. A reduced tillering period will help the crop to mature under temperatures that are lower than normal. High temperature during heading is detrimental, however, and during the ripening phase reduces the grain-filling period. Protection against high temperatures has received considerably less attention than cold temperatures. This is because in the vegetative phase rice can tolerate temperatures of 44°C–45°C (Abrol and Gadgil, 1990). Unlike low temperatures, high temperatures allow rice to be grown, though with reduced yields. Heat stress can be minimized by irrigation, which exerts a cooling effect by converting sensible heat to latent heat and is the most promising and suitable measure in this context (Merva and Vandenbrink, 1979).

Sowing of pre-germinated seeds is routinely practiced in rice culture. High pre-sowing treatment temperatures induce early flowering, reducing the time to flowering to as little as 60 days in some varieties (Parija, 1943). Therefore, in incubating rice seeds to induce early germination for sowing in warm

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Types of cool weather damage to rice plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before nursery</td>
<td>Retarded cultivation</td>
</tr>
<tr>
<td>Nursery stage</td>
<td>Inferior germination and growth; withering and seedling rot; delay in transplanting due to freezing immediately after removing a cover on the protected nursery</td>
</tr>
<tr>
<td>Early stage: transplanting, tillering, panicle formation</td>
<td>Delay in transplanting; poor rooting; discoloration of leaves; decrease in tiller number; delay in growth and formation of young panicles; reduction in size of panicles</td>
</tr>
<tr>
<td>Panicle initiation to booting</td>
<td>Degeneration of rachis branches; decrease in spikelets; cessation of spikelet growth; delay in heading; non-heading; browning of leaf sheath</td>
</tr>
<tr>
<td>Heading stage</td>
<td>Delay of heading</td>
</tr>
<tr>
<td>Flowering stage</td>
<td>Delay of flowering, non-fertilization and non-flowering of lower spikelets</td>
</tr>
<tr>
<td>Ripening stage</td>
<td>Incomplete ripening; discoloration of unhulled rice grains; cessation of ripening due to early frost</td>
</tr>
</tbody>
</table>
weather, care should be taken to cool the temperatures of germination rooms to wet bulb temperature by injection of moisture from wet mats.

10.6.4.2.5 Mitigation measures, crop insurance

Covering risks in rice crop production by crop insurance is a mitigating measure. The fraction of farmers in developing countries who have crop insurance coverage is very low, however. For example, in India, only 14 per cent of the farmers are covered by crop insurance. In the Philippines, crop insurance covers only land preparation and establishment. To be meaningful, crop insurance for rice must cover all farmers and all the risks, from preparation of the nursery to harvest of rice. Insurance premiums will have to be higher for areas with unstable crop production. Higher crop insurance premiums would be an unbearable burden for farmers in areas of low rice yields with high interannual variability. Therefore, if crop insurance companies charge higher premiums, the crop insurance premiums or the difference in the cost of these premiums compared to the lowest premiums charged will have to be borne by governments. Such payment on behalf of farmers by governments does not attract the charge of subsidization of uneconomic crop production under the World Trade Organization (WTO) regulations.

Agroclimatic analyses using past series of meteorological data can help assess for any given area, season and crop, the extent of interannual variability in rice crop production on a relative basis. This approach is justifiable on the ground that differences among rice cultivars with respect to weather parameters are differences of degree, rather than of type. Use of satellite imagery for crop monitoring, calibrated against agrometeorologically analysed ground truth, has the potential to provide an independent verification for crop insurance firms of claims for crop yield losses. Thus, agroclimatic analyses have a role to play in the setting of rational insurance premiums for rice and in providing an unbiased picture for crop losses in rice on a regional and seasonal basis.

10.6.4.2.6 Weather forecasting

Even with careful agronomic planning for rice, through microscale agroclimatic analyses to suit local climate, the start of the rice season can be negatively affected by the variability of regular weather systems, such as monsoons, and irregular weather phenomena, such as El Niño and La Niña. Standing rice crops are subjected to weather vagaries on a year-to-year basis. Technologies to cope with climatic variabilities and weather anomalies are available. The vulnerability of rice production to weather can be considerably minimized if expected weather situations can be accurately forecast on a long-range basis and the forecasts conveyed to farmers. The long-range weather forecast (LRWF) will give rice farmers sufficient time to organize and implement appropriate contingency cropping measures, at the start of the season, in tune with the expected weather. Due to the lack of sufficient data to validate its accuracy, LRWF technology is far from suitable for operational adoption in pre-seasonal planning of rice culture. Again, at present LRWFs only forecast what the anomaly of a weather situation will be at the end of the forecast period and give no indication of the temporal distribution by which the forecast anomaly will be realized. Hence they are of no operational use except for indications relating to early, normal or late onset of the season. Once the rice crop is planted, the production resources and technology get committed to a particular course of action. Medium-range weather forecasts, however, if they are properly interpreted for their likely agronomic consequences in light of the actual stage and state of a standing crop and quickly transmitted in real time, will help rice farmers to cope with and/or counteract the impacts of unfavourable weather and take advantage of favourable weather situations.

10.6.4.2.7 Improvement measures

The development of simple implements for intercultural operations, especially weeding, rapid harvesting and post-harvest handling (Pantastico and Cardenas, 1980), is a much-needed improvement measure. Biological improvement measures include breeding varieties for enhanced drought, heat and cold tolerance; with increased resistance to lodging; with morphological adaptations for better interception of solar radiation; with physiological improvements for more efficient use of CO₂ and solar radiation in photosynthesis; and resistance to specific pests and diseases.

10.6.5 User requirements for agrometeorological information on rice

Due to complex combinations of climate regimes and cultural systems of rice, the rice farmer’s needs for agrometeorological information might be more specific in some respects than those of other farmers. At present, agricultural weather forecasts and advisories derived from these forecasts are being provided on the basis of the existing agronomic scenario of rice. The tacit assumption in this approach, which is
that the existing scenario is either optimal or unalterable, needs to be examined. Rice climate classification is the starting point to maximize and minimize, respectively, the positive features and hazards of local climate (WMO, 1983).

### 10.6.5.1 Rice climate zones

Rice climate classification involves the delineation of zones with intraregional differences in times and duration of the rice cropping period and potential yield levels under irrigated and rainfed conditions. Water, air temperature and solar radiation are the principal factors governing irrigated rice culture. The water factor is controllable. The other two are not. Thus the potential for irrigated rice, grown without any constraints and stresses, should first be established in various regions. Such a potential constitutes climatic fertility of rice (FAO, 1992), whose reduction due to water constraint must be assessed. Delineating these rice climate zones will help in: (i) quantitative assessment of the climatic risk due to late sowings; (ii) the prescription of cultivar-specific safe first and last dates of sowing; (iii) assessment of the probability of occurrence of critical climatic variables, such as minimum temperatures less than 15°C for early, normal and late sowings; (iv) drawing up contingency plans for late starting of the crop season; and (v) assessment of requirements for real-time agro-meteorological information that will aid the farmers on a regional and period basis.

### 10.6.5.2 Irrigated lowland rice

The methodology for rice climate classification that has been described by Venkataraman (1987) is reiterated here. The requirements for maximal yields of rice grown without any moisture constraints are a crop life duration of 135 days, with a vegetative phase of 80 days, a mean air temperature that remains in the range of 15°C to 30°C, and about eight hours of bright sunshine in the last two months of the crop. Isoquant plots giving curves of equal predicted yields for combinations of minimum temperature and solar radiation during the ripening period (30 days after flowering) have been given by Seshu and Caddy (1984). Solar radiation is linearly related to bright hours of sunshine. Thus, from climatic data of actual or derived radiation and minimum temperature, the yield potential of rice can be assessed on a monthly basis. The month preceding the optimal ripening month can be assigned to the reproductive phase if it has seven to eight hours of bright sunshine. The 80-day period preceding the reproductive month can be assigned to the vegetative phase. By repeating this process for all months, one can arrive at the times and duration of rice crop periods for various levels of productivity. There may be overlapping periods for the same level of productivity. In carrying out this exercise, one should bear in mind that for irrigated rice the start of the season is dictated by the date of release of water for first irrigation. The local traditional practice will give a real-time picture of the availability of water for the start of the rice season. Therefore, commencement of the vegetative phase cannot be earlier than the traditional first date of irrigation. Delineation of times and duration of rice crop periods for various levels of productivity at a network of stations can help in the demarcation of climate zones for irrigated rice.

### 10.6.5.3 Rainfed lowland rice

For rainfed rice climate zones, rainfall over weekly or dekadal periods has to be considered. In excess of these periods, the interannual variation of rainfall is such that one has to work in terms of probabilities and consider minimum assured rainfall amounts at various percentage probabilities. Fifty per cent probability is an acceptable risk levelling rainfed farming. Thus, first of all, at the 50 per cent probability level, the commencement can be taken as the week/dekad in which cumulation of rainfall minus evaporative power of air reaches the water requirement for field preparation. The end will be the week/dekad when rainfall sharply declines below the evaporative power of air. It is possible that such delineated periods may be more or less than the optimal vegetative life duration of rice crop of 80 days. If the periods exceed the optimal vegetative life duration, agromonomic technologies to ensure sowing and harvest of more than one rice crop or other crop rotations have to be addressed. If the periods are shorter than the optimal vegetative life duration, the choice of cultivars and/or sowing dates must be such to ensure that the rice crop enters the reproductive phase when rains cease.

For a standing rice crop, considering the magnitude of evaporative power of air in the rainfed lowland rice areas and the rainfall requirements to meet the transpirational need of the crop from transplanting/sowing to harvest, a weekly rainfall amount of 50 to 70 mm and a dekadal rainfall of 70 to 100 mm, depending on soil types, would be required. Agroclimatic, rainfall budgeting exercises of temporal distribution of rainfall in the delineated period can help assess the period(s) of moisture stress and excesses, the feasibility of rainfall harvest, and adequacy of the harvested amounts to meet the water needs of the standing crop.
during droughts and to raise another crop in the season that follows the rains. The results from such agroclimatic analyses at a network of stations can be used to demarcate homogeneous climate zones for rainfed lowland rice.

10.6.5.4 Biotic risks and weather hazards

For irrigated and rainfed rice, periods that promote and/or are susceptible to pests and diseases and weather hazards (storms, high winds, cold waves, heatwaves, and so on) can be delineated in each of the rice climate zones for suitable remedial, agronomic and other measures.

10.6.5.5 Forecast-based weather advisories for rice farming operations

Seasonal outlooks are usually expressed as expected deviations from normal conditions and give no indication of the temporal distribution by which the forecast anomaly might be realized. Long-range weather forecasting is still in the research and experimental stage and is far from suitable for operational adoption due to insufficient data about its accuracy. It would be prudent to advise potential users of the tentative nature of monthly and seasonal outlooks (WMO, 1981). Only medium-range weather forecasts offer scope for timely scheduling of farming operations to cope with expected weather.

The main weather-sensitive rice farming operations (WMO, 1983) are:

(a) nursery activities;
(b) land preparation;
(c) seeding/transplanting;
(d) irrigation and drainage;
(e) fertilization;
(f) crop protection;
(g) application of agrochemicals;
(h) harvesting;
(i) threshing;
(j) sun-drying and cleaning.

The weather situation, which is usually a combination of threshold values of weather parameters that affect farm operations, varies from place to place and from season to season. The current state of knowledge and evaluation of the response of the rice crop to weather variables is sufficient to lay down the threshold values of weather components such as rainfall, temperature, wind and cloudiness in relation to all activities of rice production.

Based on the combination of the several categories of sky condition, soil moisture status, leaf wetness duration, temperatures and wind speed, the Guidance Material for Agrometeorological Services to Rice Farmers (WMO, 1983) indicated 72 weather features to cover all farming operations. Inclusion of too many threshold values for each weather element increases the number of weather forecast categories. The same agronomic advisory can be given for many combinations of weather elements, however (WMO, 1983). Again, the effects of a given weather situation are critically dependent on the rice crop stage. Implementation of any recommended farm operation takes time to organize. While weather can change on a daily basis, changes in crop state and stage will be gradual. Thus, agrometeorological advisories based on medium-range weather forecasts and the state and stage of crops are issued by the agrometeorologist in consultation with specialists such as pathologists, entomologists and agronomists once a week and updated if necessitated by the perception of a change in forecast weather. The issuance of agrometeorological advisories based on rice climate zones can help users to better benefit from these in real time.

10.6.5.6 Agrometeorological forecasting

Agrometeorological forecasting is concerned with the assessment of current and expected crop performance, including crop development stages (especially maturity) and yields (quantity and quality), along with other factors affecting production patterns (WMO, 1981). For the rice crop, two of the most important kinds of agrometeorological forecasting are phenological and yield forecasts. Phenological forecasts are important because of the relationship between the impact of any given weather situation and the rice crop stage during which it occurs. This in turn decides the type of advisory to be issued and the yield ultimately achieved. Yield forecasts sufficiently ahead of the harvest, in conjunction with an advance assessment of acreage planted to rice under various ecosystems, are crucial for timely and effective management of the rice food economy.

10.6.5.7 Phenological forecasts

The most important phenological forecast is the number of days up to flowering from sowing. This can vary with varieties. For any given varietal class, successful forecasting of rice crop phenology under field conditions has been reported. The DD50 computerized rice management programme uses the concept and computation of degree-days as a tool to predict phenological events with an accuracy of plus
or minus two days (Slaton et al., 1996) and to assist rice farmers with 28 management decisions based on growth stage, including herbicide application, scouting for insects and diseases, timing of application of nitrogenous fertilizers, and the like. The described degree of accuracy is quite high; it could most likely vary quite widely in different crop areas and yearly conditions. Mall and Aggarwall (2002) reported that CERES-rice accurately predicted vegetative-phase durations ranging from 37 to 85 days as a result of variations in varieties and locations in India. Since the predictions are based on variety-specific genetic coefficients derived from observed field data, such findings do not address the problem of real-time prediction of rice phenology.

10.6.5.8 Yield forecasts

The agrometeorological forecasts of crop yields are unit area yields. They constitute a very important tool to estimate the production of a given crop in a certain region or country by knowing the area planted. There are three approaches to modelling the impact of weather on crop yields (WMO, 1981), namely, the empirical statistical approach, crop weather analysis models, and crop growth simulation models.

10.6.5.8.1 The empirical statistical approach

According to this approach, the crop yield is related to levels of weather parameters, either singly or in combination, in selected calendar periods. Owing to rainfall and/or temperature vagaries, the selected calendar periods would relate to different rice crop phases in various years. Often there is no physiological significance between the selected periods and rice yields. For rice, drastic reductions even with normal vegetative growth can occur due to weather vagaries in the reproductive and ripening phases. Assessment of weather aberrations should be based on growth phase and not calendar dates. The empirical statistical approach will give highly misleading results in almost all years.

10.6.5.8.2 Crop weather analysis models

In this type of analysis the crop itself is used as a weather integrator in parallel with crop responses to selected agrometeorological variables at various growth stages. Such studies help identify crop growth attributes, which can be used as a measure of the likely yield and assess the influence of growth stages of a crop on the extent of reduction in potential crop yields due to weather anomalies and soil moisture stresses. While they cannot per se give any yield estimates, they provide valuable inputs for designing sub-routines in the crop growth simulation models for the use of quantified crop attributes in yield assessment, and for assessing the effects of environmental stresses in terms of crop phase on the extent of reduction in yield by comparison with a non-stressed crop.

10.6.5.8.3 Crop weather simulation

The dynamic crop weather models simulate plant physiological processes, such as photosynthesis, transpiration, respiration, biomass partitioning, nutrient uptake and water use in daily time steps in a manner similar to the processes as they are visualized in the rice crop (Uchara, 1985) for conversion of seeds, water and fertilizers into rice grain and straw. Phenological stages are simulated in the models from considerations of thermal and photoperiod regimes. In crop yield forecasting, feedback information from fields on the observed stage and state of crops can then be input into the models. So only the part of the model relating to prediction of rice yield becomes relevant in real time. For the purpose of predicting rice yields, the models require individual calibration for the varieties used. The models constitute valuable research tools for studying the performance of rice cultivars under different environmental, soil and management conditions through meteorological links when weather is the only operating variable. The models, however, require cultivar-specific genetic coefficients for many parameters and development rates. The problem posed by varietal variations in vogue in rice culture can be overcome through the following considerations of phenological and physiological responses of rice to weather.

The dry matter accumulated in the vegetative phase is related to the final grain yield. The ratios in the quantity of dry matter available at the start of the reproductive phase among cultivars can reasonably be assumed to be the same as the ratios of duration of their vegetative phases. The percentage change in the duration of vegetative phase due to weather influences will be the same for all cultivars under the same weather regime. So the ratios will be conservative across yearly weather situations. The durations of the reproductive and ripening phases are nearly the same for all cultivars. One goal of agronomic planning is to ensure that all the cultivars are exposed to the same weather in the maturity phase. The actual quantity of dry matter produced in the reproductive phase can vary among cultivars. There will be no change in the ratios of production of dry matter in the maturity phase among cultivars, however. The change in duration
of vegetative phase at a location due to the temperature factor is never drastic. Thus, the percentage change in yield from the potential due to weather variations will be the same for different cultivars across locations and years. Therefore, validation of the models at a few locations and for a few cultivars can be used for assessment of yields of different cultivars across seasons and locations under irrigated and non-limiting nutritional conditions. The models assume that diseases and pests are absent, that there are no adverse soil conditions, and that extreme weather events such as typhoons and the like do not occur. Reductions in yield of rice often arise from biotic stresses and hazardous weather. So the final yield estimates have to be adjusted for losses due to biotic and abiotic stresses.

10.6.5.9 Biometeorological models

A combination of the crop weather analysis approach involving the use of yield-determining attributes, such as spikelet number at heading, and dynamic simulation models for assessing total dry matter accumulation may be necessary for predicting rice yields.

10.6.5.10 Field-level data series

For both rainfed and irrigated rice, yield prediction models must be validated at the level of technology the farmer uses, which on the whole is continuing to rise. Thus, for rice-yield forecasting, availability of data from recent years on yields of typical cultivars recorded on farmers' fields by properly designed crop-cutting experiments, and the archiving of such data for ready retrieval and use, are necessary. In the case of rainfed rice, the yield level will depend on the availability or absence of facilities for collection and re-use of runoff from rainfall. As a result, yield data for purely rainfed conditions and for rainfall harvest and re-use conditions have to be recorded separately.

10.6.5.11 Use of forecast weather data

Rice yield forecasts need to be issued preferably two months in advance of crop harvest and definitely at least one month in advance. Therefore, for use in the models, forecast levels of various parameters have to be provided on a weekly basis for a month or two in advance. As in weather forecasting, values of analogous years or climatic normals or forecast values can be used. It is very difficult to find a year that is completely analogous to the year under consideration. Instead of using climatic normals, it is preferable to use forecast probabilities of parameters, principally temperatures and sunshine/solar radiation.

10.6.6 Agrometeorological services relating to rice

The national weather services have the mandate to meet the climatic data needs for crop planning and the weather forecast requirements for agricultural operations. The forecast service is a matter of great daily urgency for farmers. Weather forecasts cannot be issued only for or even with special reference to rice, however. So agrometeorological services for rice farmers involve the following questions: “Who provides what information where?” “Who receives and interprets the routine flow of various types of forecasts with reference to available rice crop information and issues agronomic advisories?” “How do farmers access this information?” The answers lie in rice farmers’ forming their own associations to appoint agents and/or seek advice from agrometeorological consultants who understand weather relations of farm operations, pests and diseases, and the like in relation to all crops and hence can interpret the forecasts in terms of rice and issue rice-specific advisories.

10.6.6.1 Agrometeorological extension for rice farmers

Medium-range weather forecasts (MRWFs) by themselves can be used in scheduling farm work in rice. Rice farmers can also take advantage of updated MRWFs. Rice farmers in developing countries are ill equipped to take action on daily weather forecasts or updated MRWFs on their own, however. Thus, it would be ideal to have working arrangements for cooperation between the meteorological centres and agricultural cooperatives and/or agricultural extension services, as well as local “extension agrometeorologists” who are trained to translate the forecasts in terms of farm operations for rice into a language understood by the farmers. The majority of rice farmers located in tropical areas are too poor to form associations and not literate enough to benefit from information conveyed through print media, Websites or text messages. The governments should, therefore, enable the rice farmers to form cooperatives and facilitate conveyance of agrometeorological advisories through community radio and television channels. In organizing such a set-up, the experience gained by rice farmers from a few countries in organizing self-help entities to derive benefit from weather-based precision rice farming should be of help and is described below.

10.6.6.1.1 Brazil

A three-month weather outlook is issued by a team of meteorologists, agrometeorologists and agronomists
to help rice farmers take several planning decisions in the southern region of Brazil (Berlato and Fontana, 2003). The Web page (in Portuguese) of the Laboratory of Agrometeorology (http://www.cpact.embrapa.br/agromet) offers some agroclimatological products for irrigated rice in the state of Rio Grande do Sul. These products include agroclimatic zoning for potential productivity and climatic risk according to the sowing period; the probability of minimum air temperature harmful to rice; a three-month weather forecast; management techniques to minimize the impact of the forecast weather; and application of the degree-day method to help farmers apply nitrogenous fertilizers at panicle differentiation. Maps are provided indicating the climatologically estimated dates of panicle differentiation for groups of short- and medium-cycle varieties, for emergence dates at 10-day intervals. Detailed information can also be found in a publication (Steinmetz et al., 2004) available as a PDF file.

10.6.6.1.2 United States

The computerized rice management programme called DD50 caters to rice farmers in the United States, principally in the states of Arkansas, Louisiana and Texas. The programme is open to individual rice farmers, farmers’ agents and consultants. More than 2 000 Arkansas rice growers on more than 60 per cent of the state's rice area (Slaton et al., 1996) use the programme. To participate in the programme, farmers submit the variety, area sown and emergence date of each rice field to their local county extension office. Agents automatically receive a copy of all reports (via e-mail) generated for their county, regardless of who initiated the report (producer, agent or consultant). DD50 provides decision-management aids based on planting date, variety and weather information.

The main data contributed are the weather information provided by the National Weather Service and updated daily to the weather Website of the University of Arkansas Cooperative Extension Service. This programme utilizes the concept of degree-days (DD) or heat units to estimate when a certain stage of the rice crop will occur. The basic data used are: the emergence date(s) and the variety (or varieties) used by the farmer; the thermal units required to reach the main development stages of the most important varieties, which are determined in the research stations; and long series (30 years) of past daily maximum and minimum air temperature data and the current year’s data for the crop season. In general, the events predicted by DD50 are held to be accurate within plus or minus two days (Slaton et al., 1996). Nowadays, this programme assists farmers with 28 management decisions based on growth stage, including herbicide application, critical times to scout for insects and diseases, and N application. For example, the ability to predict growth stage, specifically internode elongation (IE), has reduced the physical labour required to sample fields to determine the accurate time for midseason application of nitrogenous fertilizers.

At the beginning of the season, the DD50 operates using the 30-year temperature averages. Then it is continually updated with the current year's temperature data to improve accuracy. Updated DD50 printouts are provided to farmers when temperature-based phenological dates are expected to deviate from the 30-year average by three or more days. In the three states mentioned, only registered users can avail themselves of the benefits of the DD50 programme.

10.6.6.1.3 Japan

In the Tohoku region of Japan, yield fluctuations of rice are strongly influenced by fluctuations in summer mean temperatures (Hayashi and Jung, 2000). An example of the use of crop model and meteorological data in monitoring the rice development and cool-summer damage in the Tohoku district of Japan has been reported (Yajima, 1996). The results obtained by combining the models on development stages and on spikelet sterility with the crop, meteorological and geographical data, emphasize the importance of the use of the crop model for the monitoring and forecasting of rice development stages and spikelet sterility at the regional level or in areas affected by cool-temperature damage. Extension staff can easily use this method to provide information on the possible occurrence of spikelet sterility in particular areas that may enable farmers to take the necessary measures to minimize the yield reduction due to cool temperature. An early warning system against cool-summer damage in northern Japan is in operation (Yajima, 2003).

10.7 AGROMETEOROLOGY AND SORGHUM PRODUCTION

10.7.1 Introduction

Sorghum (Sorghum bicolor (L.) Moench) is a cereal grass native to sub-Saharan Africa that 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, W.C. Kaffir corn, 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 5,000 years ago and since that time, continuous human intervention has led to the development of the crop.

Sorghum is well known for its capacity to tolerate conditions of limited moisture and to 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 temporarily 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 economically viable 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, sorghum is the fifth most important cereal crop grown in the world after wheat, rice, maize and barley (FAO, 2006).

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (tonnes)</th>
<th>Area harvest (ha)</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>9,847,680</td>
<td>2,301,470</td>
<td>4.279</td>
</tr>
<tr>
<td>Nigeria</td>
<td>8,028,000</td>
<td>7,073,000</td>
<td>1.135</td>
</tr>
<tr>
<td>India</td>
<td>8,000,000</td>
<td>9,400,000</td>
<td>0.851</td>
</tr>
<tr>
<td>Mexico</td>
<td>6,300,000</td>
<td>1,909,090</td>
<td>3.300</td>
</tr>
<tr>
<td>Sudan</td>
<td>4,228,000</td>
<td>8,000,000</td>
<td>0.529</td>
</tr>
<tr>
<td>Argentina</td>
<td>2,900,000</td>
<td>558,000</td>
<td>5.197</td>
</tr>
<tr>
<td>China</td>
<td>2,592,800</td>
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<td>3.855</td>
</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Brazil</td>
<td>1,529,600</td>
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</tr>
<tr>
<td>World</td>
<td>58,620,842</td>
<td>44,703,950</td>
<td>1.311</td>
</tr>
</tbody>
</table>

Sorghum is 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 and 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), while 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), also contribute to this. The ensilage of sorghum also usually prevents stock losses from prussic acid poisoning.

The flowering panicles of the plant are used as brushes, brooms and whisks, while the stems are used for weaving fences and 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, and 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 United States 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 desirable only because it was unpalatable to birds, a great pest in sorghum production. High-tannin sorghum is still grown where birds represent a problem for production. In the United States, reduced-tannin sorghum has been developed, which has led to an improvement in its use for food by as much as 30 per cent.

Sorghum grains have a structure very similar to that of maize, although they are smaller and generally oval in shape. Both sorghum and maize 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 per cent protein, 75 per cent starch, 4 per cent fat and 4 per cent minerals. Sorghum has a very hard kernel, which makes it resistant to disease and physical damage, but also harder for animals to digest. To combat this characteristic, it is ground, cracked, steam-flaked and/or roasted, which enhances its nutritional value by 12–14 per cent.

10.7.2 Agroclimatology of sorghum

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

(a) Climatic factors: rainfall (water management), solar radiation, photoperiod and temperature;
(b) Soil factors: chemical and physical soil properties and topography;
(c) Crop management: fertilization strategy, plant arrangement, plant population, weed and disease control, and so on;
(d) Genotype: potential of production, adaptability to the environment.

10.7.2.1 Rainfall – water management

Of all the factors that affect agricultural production, the deleterious effects of climate are the most difficult to ameliorate. Add to this the variability and unpredictability of climatic factors and this becomes the main risk to production. Abiotic stresses such as drought or excessive rainfall, very high or low temperatures, low insolation levels, and so forth, 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 plant’s growth cycle generally being the single factor that limits crop yield (Chiroma et al., 2006).

Water constitutes, in general, about 90 per cent of a plant’s mass and is important for internal transport (minerals, photosynthates, and so on), temperature regulation, as a milieu for biochemical reactions and as a solvent; it also affects plant structure through plant 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, morphological, physiological and biochemical. Drought conditions can affect a plant’s water and nutrient absorption, seed germination, opening and closing of stomata, photosynthetic activity, transpiration, enzymatic activity and several other metabolic and physiological processes. The more obvious general effect with respect to water deficit, however, 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 favourable again for growth. Late drought stops leaf development, but not floral initiation.

To obtain high yields, cultivars with a cycle from 110 to 130 days require 450–650 mm of water (FAO, 1979). In order to maximize sorghum yields, soil moisture should be maintained above 55 per cent of the available water capacity in the
rooting zone of the soil profile throughout the growing season. When the growing period is long, stalkling cultivars are capable of recovery through 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 in the resultant yield can be partially compensated for by additional stalks with spikes (FAO, 1979).

In general, the greatest water consumption coincides with the period in which sorghum plants present the greatest height and leaf area index. Severe water deficits during this vegetative growth phase reduce the plant’s mass increase and leaf area development; this affects grain yield, even 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.

10.7.2.2 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 coordinate 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, namely, 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, that is, 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.

10.7.2.3 Temperature

Temperature is an important factor that affects sorghum growth and is directly related to solar radiation. Soil temperature affects the plant’s growth: it influences root growth and metabolism and modifies 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 on the order of 10 per cent when they covered the soil with clear plastic, which kept the soil temperature about 2°C higher during the growth period. Peacock (1982) and other researchers have suggested that the best temperature for germination is between 21°C and 35°C and that temperatures of 40°C to 48°C have been lethal. Adams and Thompson (1973) also observed that when the soil temperature falls from 26°C to 23°C in the pollination and grain 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 is necessary for all physiological processes to occur. Low temperatures (<10°C) cause reduction of the leaf area, stalking and plant height; decrease dry matter accumulation; and delay flowering, possibly owing to a reduction in chlorophyll synthesis and consequently photosynthesis. When compared with corn, sorghum is more tolerant of high temperatures and less tolerant of low temperatures. When the average daily temperatures are lower than 20°C, there is prolongation of the growth period from 10 to 20 days for each 0.5°C of fall in temperature. High and low temperatures stimulate basal stalking. Low and high temperatures (<15°C and >35°C) during 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°C to 43°C when the relative humidity is between 15 and 30 per cent. High temperatures, six to nine days after anthesis, reduce seed weight. Low temperatures during
anthesis affect panicle development, causing spike sterility through the effect on meiosis, which provokes 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°C to 23°C and then declines with temperatures over 34°C. Eastin et al. (1976) noted that night temperatures of 5°C above the optimum temperature reduced yield grains from 25 per cent to 33 per cent, and 10°C above the optimum reduced the yield by 50 per cent. 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 have been contradictory. While most authors cite optimum values around 33°C–34°C, Norcio (1976) established the optimum temperature for sorghum development in field conditions to be between 35°C and 42°C, although he emphasized that there are differences among 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°C to 68°C. Soil temperatures of 18°C at 5 cm soil depth for three consecutive mornings are recommended for even, vigorous seedling emergence (Amathauer, 1997).

10.7.3 Other background information on sorghum

Sorghum is a C₄ plant (fixes carbon dioxide into 4 carbon acids) of tropical origin. It is productive at high light intensities and high temperatures such as 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-climate) varieties. The crop requirements are very similar to those of corn, except that 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 hence can succeed in arid soils.

While the sorghum crop prefers a slightly to moderately acid soil, some cultivars will grow with a soil pH as high as 8. Sorghum 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 crop’s performance considerably despite the moderate tolerance of sorghum plants to saline soils. A basic dressing of nitrogen, phosphorus and potassium 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 plant’s first growth phase (planting until panicle initiation), rapid germination, emergence and plant establishment are 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, even though these are slower in fodder sorghum varieties 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 seed filling. The final yield is a 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 40 cm to 400 cm. Temperature, water deficit and soil nutrient status can affect the expansion rate of leaves, leaf area duration and plant height, though this effect is mainly seen in photoperiod-sensitive genotypes. The growth habit of sorghum is similar to that of maize, but sorghum presents more side shoots and a more extensively branched root system. The root system of sorghum is very fibrous and can extend to a depth of up to 1.5 m, even though the plant extracts 75 per cent of its water from the top metre of soil. As a result, 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 plant’s ability to survive drought by limiting its root system development. Since these plants are physiologically suited for growing in hot dry areas, it
10.7.4 **Management aspects of sorghum in various environments**

Productivity of the sorghum crop, when measured in terms of dry matter production, depends on the difference between photosynthate accumulation and photosynthate losses through respiration. Any factor that modifies photosynthesis and respiration can have both positive and negative effects on productivity. This includes 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 on temperature. Peacock and Heinrich (1984) showed that leaf emergence (leaves/day) increased when the temperature rose from 13°C to 23°C. It was also found that when the day and night temperatures climbed from 20°C/15°C to 35°C/30°C, there was an increase in leaf emergence. These authors also found that leaf expansion increases up to 34°C and that above this level, the leaf expansion rate starts to decrease. They also showed that below about 15°C, leaf expansion ceases. Generally, the leaf expansion rate has been observed to be approximately 60 cm² plant⁻¹ day⁻¹.

The influence of temperature on the growth of roots has not been studied extensively and the few existing results suggest that the growth–temperature relationship is similar to 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 that consider all the possible interactions that affect yield. There is no single set of practices that guarantees high yields, however. What is necessary, though, 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 have a positive yield effect should address the following:

(a) The creation of good soil drainage and water storage, which encourage root system development. Such practices may include no-tillage systems and crop rotation;

(b) An increase in the soil depth available to roots and enlargement of the water extraction layer in the soil through production of a larger soil water reservoir and, consequently, greater water availability to sustain plant growth during short periods of drought;

(c) Elevation or re-establishment of the nutritional level of the soil, so that it is appropriate to the crop yield required;

(d) The use of cultivars adapted to the region;

(e) Planning of 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. Water availability is particularly important;

(f) Attention to pests and diseases that may reduce yield;

(g) Weed control in order to reduce competition for water, nutrients and light.

In regions with irregular rainfall 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 help 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 order to increase 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: this improves soil porosity and soil structure and increases the proportion of the soil water available to the plant. These factors, coupled with the reduced soil evaporation and increase in water infiltration rate, allow larger water storage in no-tillage system soils compared with 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 and improves the soil's cationic change capacity, in addition to 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 also allows greater transpiration losses, even though the
transpiration ratio (g water/g dry weight increase) for C₄ plants such as sorghum is low.

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

Insect pests and diseases are important factors to contend with in sorghum production. In some regions, insects can be a major limiting factor in grain sorghum production. Common soil insects, stem borers, aphids, green bugs and shoot flies 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 moulds, 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 programmes can minimize losses from insects and diseases. These measures include: planting tolerant cultivars, conducting crop rotation, managing crop residues properly, timely harvesting, biological control and accurate and timely application of insecticides and fungicides.

Besides insects, birds are a major pest that can reduce yield considerably. Several types of birds can infest grain sorghum during the period from 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). Cultivating hybrids with a higher tannin content, but also growing the crop in large field blocks, may help to combat birds.

Although sowing time usually does not have an effect on production cost, it affects the yield and thus the farmer’s profit. Decisions affecting the time of sowing should be based on the risk factors that can be minimized, as these represent efficient planning activities relating to production. In addition to management practices, however, sorghum productivity is a function of several integrated plant factors, such as the 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 – 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 neither genotypic nor environmental effects are independent. Hence the importance of the sowing time is mainly with respect to the crop cycle, namely, 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 and so forth, 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 that reduce its productivity considerably. Therefore “sowing time” refers to the period in which the crop has a high probability of growing in soil and climatic conditions that are both favourable.

Although it is practically impossible to control the climate, it is possible to define the season with the 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 that are more sensitive to water deficits.

10.7.6 **Examples of agrometeorological services relating to sorghum**

In the area of agrometeorological services, the climatic risk zoning of sorghum developed in Brazil has been contributing to sowing times that present a smaller climatic risk to the crop. In Brazil, sorghum is generally cultivated in the summer following another crop – the sowing date depends on the growing season of the preceding crop as well as on 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: (a) the characteristics and distribution of precipitation; (b) 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); (c) the water consumption of sorghum in its different growth phases; and (d) the cultivar’s life cycle (Farias et al., 2003). With this baseline 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 10.7.1 shows climatic risk maps in relation to sorghum in the Paraná State, Brazil. These studies were carried out for the main regions of sorghum production and this information now constitutes an important tool for providing guidance with regard to the sowing date, as well as agricultural policies, since the information can be used to establish subsidies, credit concessions and agricultural insurance. All of the information for sorghum, as well as for some others crops, is available at http://www.agritempo.gov.br. Besides having information about climatic risk zoning, this Website also contains other important agrometeorological 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 one to define areas that are subject to economic risk because of pests and diseases whose appearance is related to climate.

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

Another example of agrometeorological services relating 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 (monocultured) 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.

![Figure 10.7.1. Climatic risk zoning for sorghum in Paraná State, Brazil: water risk during six sowing periods, with a cultivar cycle of 120 days and an available water capacity in the soil of 50 mm](image-url)
The cereals are grown for consumption and cash. Intercropping components adopted by farmers are grown at low densities in order to minimize 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 sole and intercropped crops were sown and rooted beyond 1 m in the loose sandy soil. Sorghum root production was greater than for millet, while both cereals produced greater root densities than cowpea. Overlay 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 it did as a sole crop, 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 comes from Sudan (Ibrahim et al., 2000, 2002). In the Gezira irrigation scheme, modern irrigation approaches and less field attendance, especially for sorghum and groundnut fields, were accompanied by significant symptoms of water waste. A serious debate among authorities on a return to traditional irrigation methods or other possible solutions needed quantification of the wastes concerned. At their request, a quantitative study was undertaken on irrigation that was also meant to suggest ways to improve the situation in a manner compatible with the local socio-economics of the use of sharecroppers. To possibly strengthen, but at least to verify, the arguments of those who wanted 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 accomplish this.

The study revealed wastage of irrigation water in both irrigation methods, but at different rates and in a different manner for each crop. The waste was higher in unattended irrigation of both sorghum and groundnut. Even much of the consumptive use was economically ill-invested in non-fertilized sorghum, because with higher inputs the same amounts of water would provide higher returns. The application differences were mainly due to the watering methods, causing different amounts of standing water, and the methods for 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 (such as weeding) in the scheme was crucial for obtaining the same or somewhat higher yields with other external inputs remaining at the present low levels. The most important measure in this respect would be to adopt a land-levelling programme to the practical limits possible and to apply partly or fully attended watering on small areas, as had been recommended in the traditional night storage system. A minimum practical level of standing water in the furrows during and immediately after each irrigation was desirable. The adoption of economic measures relating to the payment and price of irrigation water was also advisable.

A final example of an agrometeorological service related to sorghum also comes from Sudan (Abdalla et al., 2002a, 2002b; Bakheit and Stigter, 2004). In the country’s central clay plain, traditional subsistence farmers and small farmers who 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 under more and more pressure. This encouraged farmers in central Sudan to experiment with possible improvements to 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. The innovations derived by farmers using shallower pits (50 cm in the experiments) and applying chaff linings at the bottom and sides of these shallow pits (of at least 25 cm before compression by the stored grain in the experiments), made safe storage possible during at least two consecutive bad rainy seasons. Wide protective caps on top of the pits (extending 1 m beyond the pit diameter in the experiments), which were aimed at diminishing the chances of cracks leading water to the grain, were a necessary precaution that had been highlighted by the research experience.

Improved matmura systems have the potential to increase the food security of farmers and bolster...
their economic position. The initiatives showed that farmers in the Jebelmuoya villages could benefit from improved matmuras. Calculations indicated that improved sorghum matmuras could increase returns by up to 45 per cent, 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 these storage pits provided against theft and fire.

10.8 AGROMETEOROLOGY AND WHEAT PRODUCTION

10.8.1 Introduction

From the earliest days of human civilization, wheat has played a significant role in nearly all societies. It was one of the first plants to be domesticated and cultivated by humans, possibly between 18 000 B.C. and 12 000 B.C. The domestication of wheat was critical in the transition from hunter-gatherer groups to stabilized societies with an agrarian foundation. Initial wheat production flourished in the “fertile crescent” region of the Tigris and Euphrates rivers. Since domestication, wheat production has dramatically expanded, so that wheat ranks as one of the most important crops worldwide and has the widest geographical distribution of any crop. Its unique gluten content and associated breadmaking properties, along with use in many food products, assure its continued role in society.

10.8.1.1 Classification of wheat

Wheat belongs to the genus Triticum and groupings within this genus are based on the number of chromosome sets. Only three Triticum species have commercial significance: common bread wheat (T. aestivum); durum wheat (T. durum), which is used mainly for pasta; and club wheat (T. compactum), which is used primarily for pastry and household flour. Most wheat grown throughout the world is the hexaploid T. aestivum.

A number of derived species have been produced using Triticum. A cross of Triticum with rye (Secale) has produced Triticale; crossing with Agropyron has produced Agroticrum (Morris and Sears, 1967); and a cross with Haynaldia has produced Haynalticrum. Some of this material has provided valuable genetic information or has contributed disease and insect resistance. The successful development of such wide crosses may be useful to the development of a perennial wheat and to gene diversity of cultivated wheat, but many are not useful at present.

Wheat is often characterized as being a “winter wheat” or “spring wheat”, with the normally recognized distinction being that spring wheat does not require a cold period (called vernalization) for the formation of flower primordia. Cultivars vary greatly in their vernalization requirement, and some “spring wheat” cultivars have a short vernalization requirement. Given the vernalization requirement of winter wheat, it is often planted in the fall and receives the vernalizing temperatures in late fall and early winter. Two problems can occur, however: (1) winterkill can occur at high latitudes; and (2) late frosts in the spring can significantly reduce yields as a result of damage to developing flowers. Winter cereals are preferred over spring cereals wherever it is possible for them to survive the winter period as they tend to produce higher yields (Hunt, 1980a, 1980b; Salmon, 1917).

Considerable research has gone into developing greater cold tolerance and altering management via fertilizer (especially at planting), tillage/residue cover (influencing snow catch), and planting date to reduce winterkill. As plant breeders succeed in producing cultivars with greater winter hardiness and as cultural practices provide greater protection against winter injury, the limits to winter wheat production will move into more extreme areas and may displace spring wheat. In North America, for example, increased winter hardiness has allowed winter barley to become more firmly established around the Great Lakes region (Hunt, 1980a). Except in favoured areas of the northern Great Plains region of North America, winter wheat production is unlikely to expand unless winter survival becomes more reliable. In the past, quantum jumps in winter hardiness have not occurred because of the multiplicity of genetic factors involved in winter survival.

A key advancement in wheat production has been the introduction of semi-dwarfing genes, and indeed this was fundamental to the Green Revolution because it allowed higher fertilizer inputs without the associated yield loss due to lodging (namely, tall stems falling over). The introduction of semi-dwarfing genes has changed the partitioning between the canopy and roots, and the harvest index (the ratio of the seed weight to the above-ground weight), among other traits (for example, Baenziger et al., 2004; Miralles and Slafer, 1995).
A notable development of the last decade has been the explosion of information being derived from molecular biology and genome mapping, allowing characterization of genes and genomes beyond just their phenotypic effects. Positional cloning of important wheat genes is rapidly advancing. For instance, three vernalization genes in wheat (VRN1, Yan et al., 2003; VRN2, Yan et al., 2004, and VRN3, Yan et al., 2006) have been cloned, as well as the Ppd-H1 gene for photoperiod response in barley (Turner et al., 2005) and the Ma3 maturity locus related to phytochrome B synthesis in sorghum (Childs et al., 1997). Gene networks controlling flowering are quickly emerging for crop plants such as barley (Laurie et al., 2004).

10.8.1.2 Adaptation of wheat

Wheat is among the world’s most widely cultivated crops, occupying over 22 percent of the area devoted to crop grain production (FAO, 2007). It is harvested every month of the year somewhere in the world, from as far south as Argentina and as far north as Finland, and it is grown over a substantial area in almost every country of North and South America, Europe and Asia (Table 10.8.1). Wheat, a C3 crop, is considered a cool-season grass. Therefore it is concentrated in areas between 30° N and 60° N latitude and 25° S and 40° S latitude (Briggle and Curtis, 1987), although varieties that can thrive within 20° of the Equator or lower at higher elevations have resulted from continued development of photo-period-insensitive wheat cultivars derived by the International Maize and Wheat Improvement Center (known by its Spanish Acronym CIMMYT, for Centro Internacional de Mejoramiento de Maíz y Trigo), along with other breeding efforts. Production, in terms of harvested area, remains remarkably consistent among countries, as rankings of countries changed little between 2004 and 2005 (Table 10.8.1).

Wheat is the cereal crop that accounts for the greatest volume of international trade, yet it is subject to political and economic factors, in addition to its environmental adaptation. Producers are guided in their decision-making process by the net returns to environmental adaptation. Producers are guided in their decision-making process by the net returns to

10.8.2 Influences of agroclimatological variables on wheat

As with all crops, climatological factors such as temperature, precipitation, solar radiation (intensity, photoperiod and quality) and wind are important in influencing wheat production. While these and many other factors influence yield, the close association between yearly/seasonal weather and yield has often been noted. Therefore, weather (particularly temperature and precipitation) would likely be the first factor to explore in explaining differences in yields of over 100 per cent between 2004 and 2005 observed in the Republic of China and Ukraine (Table 10.8.1). As the climate continues to change in the twenty-first century, whether hotter and drier or cooler and wetter in different regions, wheat production should be impacted.

Breeding has resulted in considerable diversity of genotypes (that is, cultivars) that respond differently to the interaction of these environmental variables, and indeed, the genotype-by-environment interaction is important in selecting cultivars for specific environments. The ever-expanding genetic diversity is allowing for the expansion of wheat into new production regions. Selection of wheat cultivars, however, is still strongly influenced by the vernalization (low temperature period required to initiate flower formation) and photoperiod requirements, disease and pest resistance, and drought tolerance of the cultivar. Also, consideration of extreme environmental conditions such as late spring frosts during flower formation and hot, dry weather at anthesis and early grain growth is important. As mentioned earlier, winter wheat production may be limited by winterkill at high latitudes and spring wheat by high temperatures during the grain-filling period.

Better understanding of the variable responses of wheat to the environment is gained by considering the development and growth of the wheat plant. This is necessary because wheat has great plasticity (that is, there are many ways that final yield can be reached), and both the environment and management influence the path taken to final yield. The important yield components of wheat are number of plants per hectare and tiller number per plant (resulting in number of spikes/heads/ears per unit area), number of spikelets per spike and kernels per spikelet (resulting in number of kernels per spike), and kernel weight. In many production environments, particularly semi-arid environments, number of spikes per unit area is the most important yield component, followed by number of kernels...
per spike, and least important is kernel size (for example, Fischer et al., 1977; McMaster, 1997; Shanahan et al., 1984). Final yield is the result of development which creates the yield potential (the number of spikes and kernels present in the plant), and the ability of the plant, interacting with the environment, to realize that potential by filling the grain (that is, the kernel size).

Many reviews of important developmental and growth processes exist (for example, Kirby and Appleyard, 1984; McMaster, 1997; Simmons, 1987) and will not be repeated in detail here. Several points merit mentioning, however. The first is that developmental events creating the yield potential occur throughout the life cycle of the plant. It begins with seed production in the previous year, where seed viability and size are important in successful seedling emergence. Tillering begins about when the third leaf appears and continues until the growth stage of jointing (when the plant grows from the prostrate rosette form to upright form because of stem growth). Tiller abortion generally begins at jointing, and the tillers remaining at anthesis determine the number of shoots that produce spikes. Flower primordia begin to form prior to jointing, and subsequent flower differentiation and abortion continue until anthesis. Grain set at anthesis (the successful fertilization and survival of florets) determines the number of kernels per spike. After grain set, the ability of the plant to supply carbohydrates and nutrients to the grain (which is a function of both the canopy and root system) determines the final yield and quality.

The second point is that development is orderly and predictable (Hay and Kirby, 1991; McMaster, 2005; Rickman and Klepper, 1995). The genetics
Temperature is important in all plant processes and is the dominant factor controlling wheat development (McMaster, 1997). In most discussions of temperature, the reference is to air temperature just above the canopy, with the assumption that tissue or whole plant temperature is equal, or very closely related, to air temperature. The assumption of a close relationship between air and plant/tissue temperature is normally reasonable when the plant is not under water deficits or the tissue is not below ground – the tissue meaning the roots or the crown, where the shoot apex is located until the growth stage of jointing, when the apex is elevated from the crown into the canopy and ultimately above the canopy at heading/anthesis. Recognition that the relationship is not always consistent led to interest in the 1990s and early 2000s in measuring or estimating soil temperature at the depth of the crown for use in plant-temperature response curves when the shoot apex was located in the crown. For a variety of reasons, however, it appears that using soil temperature is not necessarily more accurate than using air temperature (McMaster et al., 2003b).

Temperature response curves for various physiological processes of wheat normally follow a curvilinear pattern (for example, Cao and Moss, 1989; Friend et al., 1962; Streck et al., 2003; Yan and Hunt, 1999), with a frequent simplification of a linear segmented model approach often sufficient for many purposes (for example, Jamieson et al., 2007; Porter, 1993). Regardless of the function assumed, a minimum temperature exists \( T_{\text{base}} \), below which the rate of the process is zero. A linear development or process rate from \( T_{\text{base}} \) to a lower optimum temperature \( T_{\text{optl}} \) is often observed, and from \( T_{\text{optl}} \) to an upper optimum temperature \( T_{\text{optu}} \), the development or process rate is maximum and the rate declines from \( T_{\text{optu}} \) to an upper maximum temperature \( T_{\text{max}} \). While these cardinal temperatures are difficult to determine precisely, vary among cultivars and possibly change with growth stage, generally \( T_{\text{base}} \) is about 0°C, the optimum temperature range is between 18°C and 24°C and \( T_{\text{max}} \) is above 35°C for wheat.

Regardless of the temperature response function used, temperature effects on development and many other processes are usually quantified by some measure of thermal time, which is used as an indicator of the internal biological clock. Many equations are used in calculating thermal time, which is the time integral of a temperature response function that is accumulated over time. Often it is expressed as growing degree-days and uses daily maximum and minimum air temperatures as estimates of daily mean temperature.

In most instances, the mean monthly air temperatures are gradually changing during wheat development and growth. For example, up to jointing, temperatures are normally within the optimum range of 0°C to 25°C, but temperatures for later growth stages such as anthesis and grain filling can be above the optimal range. Therefore, a lack of yield response to temperature is not observed in many of the earlier parts of the life cycle, but often is observed for later phases (for example, Johnson and Kanemasu, 1983; Warrington et al., 1977). Of particular note for yield, temperature is very important for grain set and grain filling. High temperatures decrease grain set, increase the grain-filling rate and decrease the duration of grain filling, with the usual result being lower yield under high temperatures (for example, Herzog, 1986; Wardlaw et al., 1980; Wiegand and Cuellar, 1981). High temperatures during grain filling also often have a negative effect on grain quality (Asseng et al., 2002; Martre et al., 2003, 2006).

Discussions of wheat and temperature must include two aspects of low temperatures: vernalization and freezing temperatures/frosts. Vernalization has been well documented to vary among cultivars, and as mentioned, is commonly used to distinguish among winter and spring wheat types. Generally, a linear segmented model is used for the temperature response function, where temperatures from about 4°C to 8°C are most effective for vernalizing, with linear decreases at temperatures below 4°C and above 8°C (Porter, 1993; Ritchie, 1991).

Both spring and winter wheat seedlings will withstand reasonably low temperatures without adverse effects. Frost from just prior to jointing
(when flowers are being formed) and thereafter can severely damage the reproductive organs and result in sterile florets. A late-season frost may cause kernel discoloration, hinder development and result in lower grade and quality.

Freezing temperatures during the winter period can induce winterkill as a result of mechanical injury, desiccation of the protoplasm, chemical effects or suspension of metabolism. Salmon (1917) and Fowler and Gusta (1982) showed the importance of phosphorus in improving winter hardiness. As our understanding of the mechanisms increases and predictions improve (Fowler et al., 1999), breeding efforts may result in extending the geographic region where winter wheat may be reliably grown. Whether or not low temperatures injure plants depends on a number of factors.

One of the key factors involves the site and structure of ice crystals in the cell wall. Hardy winter wheat plants contain soluble polysaccharides that hinder ice crystal formation in the cell wall and intercellular spaces. Ice crystal formation can penetrate the cytoplasm and disrupt cell structure. Cells damaged by low temperatures have a typical water-soaked appearance, because membranes have been ruptured, allowing cell contents to flow out. Such cells become dehydrated and wilt when exposed to the sun.

Moisture content is another important factor. Winter wheat seedlings can become conditioned to survive low-temperature stress conditions through an acclimatization process associated with cell differentiation. Acclimatization involves complex biochemical changes triggered by environmental signals such as low temperatures (0°C to 5°C) and shortened day lengths. The biochemistry of the plant cell is changed from promoting active growth to promoting high stress tolerance, which involves gums and resins to resist freezing damage. The potential winter hardness of any cultivar depends on the success of these various biochemical changes or the degree of acclimatization or cell differentiation.

External moisture content is another important factor that may influence freezing susceptibility. Following a midwinter thaw, winter wheat and barley plants were more susceptible to low-temperature injury because of high moisture content in the crown (Metcalf et al., 1970).

Thawing conditions may also reduce the effect of acclimatization. Cold tolerance in winter wheat and rye was reduced an average of 5°C after two thawing and freezing cycles (Gusta and Fowler, 1977). Reductions in hardness, however, were variable.

The rate of freezing and thawing plays a role as well. A sudden drop in temperature before acclimatization has occurred or a sudden rise in temperature of frozen tissue will have a more detrimental effect than a slow drop or rise in temperature. The shoot apex is the part of the plant most vulnerable to freezing injury. The shoot apex contains the meristematic tissue that produces new leaves, tillers and inflorescence parts. The crown, containing the shoot apex until internode elongation begins, is a diverse part of the plant, and different patterns of freezing occur simultaneously in its various tissues (Everson and Olien, 1975). A protective snow cover may prevent plant cells from experiencing rapid and wide temperature fluctuations. A light snowfall lodged in the crown of winter cereals can provide some protection against damage by low temperatures.

Another factor is the duration of freezing. The longer the tissue is exposed to sublethal temperatures, the more severe the freezing stress becomes. McKersie (1981) reported that at –12°C the ability of plants to survive began to decline after 12 hours, and at –16°C after only one hour.

10.8.2.2 Precipitation

Successful cultivation of wheat involves the interplay of stored soil water and precipitation. Stored soil water at planting will be a function of prior precipitation, pre-plant tillage and residue cover management, and prior land use (namely, whether the tract was fallow, what the previous crop was, when it was harvested, and so on). Wheat is normally grown where annual precipitation averages 25 to 175 cm, but about three-quarters of the land area in wheat averages from 38 to 88 cm, and often wheat is grown in semi-arid regions with highly variable precipitation (both among and within years) and where water deficits are common.

Because yield components are developing and growing over the entire life cycle of the plant, water deficits at any time will likely reduce final yield. Obviously, a critical period of undesirable water stress is seed germination and emergence. If soil moisture in the seedbed zone is below optimal, germination and seedling emergence rates will be reduced, leading to slower and delayed emergence, which has many negative ramifications for the remainder of the growing season and final yield (McMaster et al., 2002).

The period from anthesis to maturity (and therefore grain-filling duration) is also critical in wheat yield and quality. Water deficits (particularly if coupled
with high temperatures) cause significant deterioration in pollen viability and grain set (that is, fertilization). Water deficits during grain filling not only reduce carbon assimilation rates, but increase canopy temperature via reduced transpiration rates (see temperature effects above) and canopy senescence via accelerated leaf senescence. The result is a significantly lowered yield under water deficit conditions. Even irrigation or high rainfall during this period can be insufficient to completely

...radiation and yield. Both photoperiod and quality are primarily involved in developmental events such as leaf appearance rates (for example, Baker et al., 1980) and phenology (for example, Nuttonson, 1948), although the duration of day length is positively related to the amount of daily radiation that can be important in total assimilation. Light quality in the red and far-red spectrum and photoperiod are particularly important in the phytochrome system. Photoperiod is primarily influential in controlling the phenological stages of flower formation (signalling the switch at the shoot apex from producing primarily vegetative primordia to reproductive primordia) and the timing of flag leaf appearance.

10.8.2.4 Wind

Wind has many impacts on wheat production. It influences the energy balance of the canopy and soil surface, altering both evaporation and transpiration, so that it influences water and temperature conditions of the plant (Grant et al., 1995; McMaster et al., 2000). As mentioned previously, wind can significantly reduce grain set, and therefore yield, if hot and dry winds occur during the period of pollination. This is a common problem in many semi-arid wheat production regions.

Wind can also result in harvest losses due to lodging (stems falling over due to wind). This problem is most common for standard tall cultivars grown under high nitrogen conditions, as the stems tend to grow tall and are more easily knocked down by wind or other disturbances. For this reason, cultivars with semi-dwarfing genes are commonly used because of the reduced stem height under high nitrogen conditions and the reduction in lodging potential.

10.8.3 Management aspects of wheat production in various climates

A positive relationship between spike density and yield is often found up to fairly high densities with a slight negative relationship at very high densities (for example, Briggs and Aytenfisu, 1979; Ciha, 1983; Darwinkel, 1978, 1980; Holliday, 1960; Laloux et al., 1980; Shanahan et al., 1984). Spike density is a function of planting rate, seedling emergence and tillers that produce spikes; in addition, all of the environmental factors discussed above influence these processes. Planting date also influences seedling emergence and tillering in several ways, however. As planting date is delayed in the fall, temperatures are
usually lower, which delays seedling emergence. Delayed emergence further slows canopy development as fewer leaves are produced in the fall. Since the appearance of tillers is related to the appearance of main stem leaves, delaying leaf appearance results in delayed appearance of fall tillers (Klepper et al., 1982, 1984). Delaying tiller appearance decreases the likelihood that tillers will survive to produce a spike, with tillers appearing in the spring more likely than fall-appearing tillers to abort before producing a spike. In general, if a tiller can survive to anthesis, it will produce a spike with reasonable yield (McMaster et al., 1994; Power and Alessi, 1978). Other factors influencing tiller appearance and survival include plant density, environmental conditions and cultivar differences. As a result, the management of final spike number must account for the complex interplay of planting rate and date, seedling emergence, environmental conditions, time of tiller appearance, and survival of tillers to produce a spike. As planting date is delayed, generally planting rates should increase to offset the fact that fewer tillers will appear and survive to produce a spike.

The preceding discussion gives some qualitative guidelines for seeding rate. Fortunately, seeding rates can vary greatly without modifying final grain yield, and it is often best to plant at higher rates given that seed cost is relatively minimal when compared to reducing the risk of having too few plants.

10.8.3.2 Soil fertilization and plant nutrition

Nitrogen, phosphorus, potassium and a variety of micronutrients are essential in wheat production. Interaction of these nutrients with the climate, soil and management (previous crops, tillage, residue cover, fertilizer, and the like) determine the availability of nutrients needed for development and growth. Soil pH is important in determining the availability of nutrients to the plant. Numerous studies have shown that growth and yield increase with fertilizer application up to some level and then generally, fertilization has no further positive influence; at very high levels of application, yield reductions can occur (for a review, see Halvorson et al., 1987). While it is difficult to over-fertilize the wheat plant from the perspective of reducing growth and yield, doing so has many negative environmental and economic implications. This has spurred a great deal of research on how (and when) to apply the optimal amount of fertilizer for the specific production environment (for example, Fischer et al., 1977). Under more uniform conditions of irrigation or high rainfall evenly spread out throughout the growing season, fertilizer recommendations are more easily made, whereas in rainfed semi-arid production regions with highly variable precipitation, a priori estimates of optimal rates are very difficult to put forward. This has promoted the concept of split fertilizer applications, where a portion is added at planting and a later application at about the jointing growth stage is “matched” to the weather to date and best guess (usually the average) for the remainder of the growing season, to meet a yield goal. Split applications reduce the likelihood of over-application of fertilizer at planting, thereby saving on fertilizer expenses and reducing the negative environmental impacts of excessive nutrient application. For winter wheat, applying nitrogen in early spring can stimulate leaf, tiller and root growth, but excessive nitrogen can result in abundant vegetative growth, increased incidence of disease and crop lodging.

10.8.3.3 Tillage and residue cover management

Tillage practices and the resulting impacts on residue cover have a great influence on the micro-environment of the wheat plant; they are increasingly being considered as an integral component of soil and water conservation practices in semi-arid wheat production systems (for example, Black and Unger, 1987; Farahani et al., 1998a, 1998b; McMaster and Wilhelm, 1997; McMaster et al., 2000, 2002; Van Doren and Allmaras, 1978). Pre-plant tillage practices usually result in increased convective exchange of water vapour at the soil–atmosphere interface, thereby reducing soil water in the seedbed zone and germination rates in semi-arid regions. Loss of standing residue cover by mechanical damage or burying of residue by tillage practices continues to affect the soil surface boundary layer for quite some time following seedling emergence. This will increase convective soil evaporative losses, creating water deficits that severely reduce yields and exposing the soil to water and wind erosion. Residue cover also influences soil temperature and albedo, further influencing both root and canopy development and growth processes. Lastly, residue cover in no-till systems increases snow catch, which both adds soil moisture available to the growing crop and reduces winterkill.

10.8.3.4 Cropping systems

Cropping systems are increasingly being integrated with changes in tillage practices, particularly in semi-arid production regions. There are many reasons for a shift from the more traditional wheat–fallow system used in many regions. Of primary importance are the impacts of creating greater
biodiversity in agricultural systems, with the benefits of better weed, disease and pest control and optimal use of available water in the system. These, and other benefits, typically result in greater sustainability of wheat-based cropping systems and higher economic returns to farmers (Halvorson et al., 1994; Nielsen et al., 2002; Peterson et al., 1993).

10.8.3.5 Weed, disease and pest management

Wheat production systems must deal with a variety of biotic factors that influence final yield. Weeds, diseases and various pests are common issues limiting wheat production. A complex interaction exists among the occurrence and degree of biotic factors and the weather (for instance, temperature, precipitation and solar radiation), soils and management practices (for example, tillage and residue cover, cropping systems selected, fertilizer and irrigation applications). The relative importance of weeds, diseases and pests can vary significantly within and among years and locations. For instance, Russian wheat aphid (Diuraphis noxia) infestations are highly variable in the Central Great Plains of the United States depending on the temperature during the winter period, with colder winters reducing the infestation level. Weed infestations vary greatly based on the tillage and chemical control practices, amount and timing of precipitation, and previous crops used in rotation (Canner et al., 2002). Often high wheat production regions such as the Pacific Northwest of the United States have much more disease problems under no- or low-tillage practices than the semi-arid regions of the Central Great Plains.

Changing climates in the future will likely significantly influence weed, disease and pest pressures on wheat production. As temperature and precipitation change, pest populations will respond accordingly. A striking example of this is the introduction of the Russian wheat aphid into the United States in 1986. It was thought that winter temperatures in the Central Great Plains were too low for the Russian wheat aphid to survive. As winter temperatures in the Central Great Plains have been warmer than normal since its introduction into the United States, however, then Russian wheat aphid has often reduced yields quite substantially in recent years. The continued warming that is predicted for this region will likely exacerbate the problem and the same is true for many other weed, disease and pest problems.

10.8.4 User requirements for agrometeorological information

There are increasing demands for timely and effective agrometeorological information for on-farm applications. Decision-makers are interested in monitoring the agricultural season to assist the farming community during adverse years, to manage risk and to provide agroclimatological information for agricultural planning. Providing agroclimatological information entails the conversion of meteorological data associated with crop yields, presentation of weather data in formats suitable for agricultural decision-making and insulation of marginal farmers with smallholdings from the adverse impact of the vagaries of weather. Meteorological data are also necessary in the development and adoption of digital technology, such as simulation models, decision support systems and commodity forecasting. These digital technologies are rapidly emerging for use by scientists, producers, agricultural consultants, agribusiness and policymakers, and rely on accurate and readily available agrometeorological data. The need for agrometeorological data will further increase with expected climate shifts.

A holocoenotic approach to agrometeorological data on a global basis would provide many benefits. Schware and Kellogg (1982) discuss how this would aid in rapidly and reliably assessing global crop yields to match areas with surplus production to areas of demand, as well as in monitoring production patterns that accompany climatic shifts. Another benefit would be to improve the judicious application of expensive inputs (such as fertilizers, irrigation and pesticide application) in terms of amount and timing.

10.8.4.1 Use of agrometeorological data in simulation models and decision support systems

Early success in crop forecasting as noted by Bauer (1979) has spurred research in the area of crop simulation modelling and decision support systems. A brief overview of some of these efforts is provided here, as these digital technologies provide an important user demand for agrometeorological data.

Early modelling efforts were commonly based on regression, or statistical, approaches, but beginning in the mid-1970s more mechanistic, or process-based, simulation models began to appear. To date, more wheat simulation models exist than for any other crop (McMaster, 1993). Regardless of the type of model, all normally require at least daily maximum and minimum temperature and precipitation, and many require daily solar radiation and wind run data as inputs. A precursor to crop simulation models was the daily canopy photosynthesis model of de Wit (1965) that was
used at least in concept in many initial simulation models (and in most even today). These models tend to be carbon- or energy-driven models that use canopy leaf area index to absorb solar radiation to produce carbon, which is then distributed to different plant components such as leaf, stem, root and seed tissue. Examples of these models include SUCROS (and earlier models of ELCROS and BACROS) (van Keulen et al., 1982), CSM-Cropsim-CERES-Wheat (Hoogenboom et al., 2004; Hunt and Pararajasingham, 1995; Jones et al., 2003; Ritchie, 1991) and Sirius (Jamieson et al., 1998a, 1998b). Beginning in the 1980s, an alternative approach towards more development-driven models was taken, leading to the creation of such models as ARCWHEAT1/AFRCWHEAT2 (Porter, 1984, 1993; Weir et al., 1984), SHOOTGRO (McMaster et al., 1991, 1992a, 1992b; Wilhelm et al., 1993; Zalud et al., 2003) and MODWht3 (Rickman et al., 1996). Often a simulation model is incorporated into decision support systems. Two examples with extensive adoption include the Australian APSIM DSS (Asseng et al., 2002) and the United States GPFARM DSS (Ascough et al., 2007; McMaster et al., 2003a; Shaffer et al., 2004).

10.8.5 Examples of agrometeorological services relating to wheat

The technology for a holocoenotic approach to global crop–climate relationships has been aided by satellite monitoring and weather collection networks. Satellite technology allows for remote-sensing of the reflected solar radiation to estimate the areas planted with specific crops and it also provides for the collection of some climatological data (Idso et al., 1977). When combined with local weather network data, this technology offers a powerful database with great potential.

One early illustration of how this functions is provided by work in the United States. Based on 8 100 surface weather observations, as well as information from satellites, United States scientists are able to compare deviations in current weather variables from the expected or long-term average (Richter, 1982). Survey data determine whether rainfall is lighter or heavier than normal; how soil moisture levels compare to those of previous years; thermal time accumulated; and if weather occurrences in general are normal or represent departures from the expected for a given area. The area planted to a specific crop, the disease situation, the level of technology and general agronomic practices can be used for yield determination and global crop estimates using various digital technology tools and other forecasting techniques. The success of this approach rests not only on weather information, but on the assembling of high-quality, historical databases for all the major regions of the world. Early efforts to use agrometeorological data in global crop forecasting showed great promise. For example, production estimates were within 10 percent of the measured estimates 90 percent of the time, and this level of accuracy was achieved 1.5 to 2 months before harvest (Bauer, 1979).

Since these early efforts, much agrometeorological information is now readily available, particularly in the Western world, via weather networks, databases and reported statistics. Indeed, there is a danger of an information overload. Agrometeorological information is available from governments, businesses and the scientific community, and ranges from local to global scales. Global climate change models have projected climate change for many regions across the globe. One caution to note regarding this information is that quality assurance and completeness are not always guaranteed. It is certain that many weather networks and databases have missing data and occasionally the methods for estimating missing data are questionable. Other chapters in this Guide provide excellent guidelines dealing with the collection of agrometeorological information and its presentation to users. They also show that in developing countries, much still remains to be done in the area of services to end-users.
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