ABSTRACT: Drought-tolerant maize hybrids currently are being marketed by several seed suppliers. Such hybrids were developed by phenotypic and marker-assisted selection or through genetic modification and tested by exposing these hybrids to various degrees of water restriction. As drought intensifies, crop yields and survival progressively decline. Water need differs among plants due to differences in root structure, evaporative loss, capacity to store water or enter temporary dormancy, and plant genetics. Availability of water differs widely not only with rainfall and irrigation but also with numerous soil and agronomic factors (e.g., soil type, slope, seeding rates, tillage practices). Reduced weed competition, enhanced pollen shed and silk production, and deep, robust root growth help to reduce the negative impacts of drought. Selected drought-tolerant maize hybrids have consistently yielded more grain even when drought conditions are not apparent either due to reduced use of soil water reserves before water restriction or due to greater tolerance of intermittent water shortages. In DuPont Pioneer trials, whole plant NDF digestibility of maize increased with water restriction, perhaps due to an increased leaf to stem ratio. Efficiency of water use, measured as dry matter or potential milk yield from silage per unit of available water, responded quadratically to water restriction, first increasing slightly but then decreasing as water restriction increased. For grain production, water restriction has its greatest negative impact during or after silking through reducing the number of kernels and reducing kernel filling. For silage production, water restriction during the vegetative growth stage negatively impacts plant height and biomass yield. Earlier planting and shorter season maize hybrids help to avoid midsummer heat stress during pollination and can reduce the number of irrigation events needed. Although drought tolerance of maize hybrids has been improved due to genetic selection or biotech approaches, selecting locally adapted hybrids or crops, adjusting seeding rates, and modifying tillage and irrigation practices are important factors that can improve efficiency of use of available water by grain and forage crops.

Key words: drought, evapotranspiration, maize, water efficiency, yield

INTRODUCTION

Following devastating droughts over 75 yr ago, the American Society of Animal Science president (Loeffel, 1936, p. 91) indicated “The development of drought-resistant crops needs emphasis.” As defined by farmers, agronomists, crop physiologists, and plant breeders, drought is an insufficient supply of water at some time during the growing season that reduces crop yield. In contrast, meteorologists appraise drought based on seasonal rainfall by the Standardized Precipitation Index (Hayes et al., 2011) whereas historians and climatologists discuss drought durations in terms of decades or centuries (Passioura, 2007).

Water is essential for both plant and animal life on earth. By reducing the food supply for animals and humans, drought increases the price for food in affluent countries but, in developing countries drought often causes starvation and political instability. According to the Food and Agriculture Organization of the United Nations (FAO, 2013, p. 1), “droughts are the world’s costliest natural disaster, accounting for 6 to 8 billion
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U.S. dollars annually, and impacting more people than any other form of natural disaster.” In regions where rainfall is insufficient, crops are irrigated using either ground or surface water, but competition between crops and humans for potable water is increasing. In some regions, crop irrigation is being restricted to redirect water for urban areas (Hawkes, 2013). Although some field crops require less water than maize, other cereal grains typically yield less than half as much digestible energy per hectare as maize, particularly in nondrought years. Yet, within the United States, approximately one-third of the hectares planted to maize experience some reduction in yield every year due to drought. During the past decade, efforts have intensified to select hybrids or alter the genetics of maize to increase drought tolerance. This paper will outline water use and needs for plant growth and the approaches being used to develop drought-tolerant maize hybrids and summarize field experience with such hybrids.

IMPACT OF WATER SUPPLY ON MAIZE PRODUCTION

Over the past 5 decades, yield of maize grain (metric tons per hectare) in the United States has averaged 22% more for irrigated than for nonirrigated hectares (Fig. 1; USDA, 2013). Based on the 2007 Census of Agriculture (USDA, 2007), irrigation was applied to 6.1% of farmland hectares, 18% of cropland hectares, and 16% of maize hectares in the United States. The National Agricultural Statistics Service (NASS) data (USDA, 2013) indicate that this percentage has decreased during the past 20 yr (Fig. 1 and 2). Maize silage yields during this same period have averaged 46% more for irrigated than for nonirrigated hectares (Fig. 2), as calculated from results of USDA (2013) surveys. The yield advantages from irrigation have been much greater in years with widespread drought (1960, 1966, 1983, 1991, 2002, and 2012), and year-to-year variability in yield has been less for irrigated than for nonirrigated maize. Certainly, geographical region and soil type may differ between hectares used for irrigation versus dry land maize production. To measure response within farms, information about grain and silage production among farms that irrigated only part of their maize grain hectares was compiled in the Census of Agriculture (USDA, 2007). Across farms where an average of 52% of the hectares had been irrigated, mean grain yield was only 4% greater than farms that used no irrigation. Based on the NASS (USDA, 2013) survey data, the increase associated with irrigation for 2007 with this portion of land irrigated should be 13.5%, so the increase in grain yield from irrigation for these farms was only 30% of that expected based on Fig. 1. Those farms producing silage, with an average of 43% of their silage hectares being irrigated, reported that silage yield was 7% greater with irrigation compared with an expected 14% (Fig. 2), only about one-half of that predicted. Presumably, farms that irrigate only part of their land are located in regions that may require minimal irrigation in a typical year. In many regions of the United States, maize production would be impossible without irrigation. Judicious irrigation during short periods of drought or in certain years in regions that normally have moderate rainfall has been suggested to lead to greater efficiency of water use than full irrigation in regions where irrigation must supply most, if not all, of the water required for maize production (Waggoner, 1994). However, the high costs associated with irrigation (e.g., land leveling for flood irrigation;
equipment and maintenance for and installation of sprinklers or drip systems) have restricted irrigation within the United States largely to western states where rainfall is low and the need for supplemental water is greatest.

Maize plants extract over 90% of their water needs from the top 1 to 1.5 m of soil (Kranz et al., 2008). Water in this soil stratum must be available either at the start of the season or supplemented by additional rainfall or irrigation during the growing season for maximum production of maize grain or silage. Based on water use efficiency over the total growing season, yield from each hectare will increase by 160 to 270 kg of grain DM or by 320 to 550 kg of silage DM for each centimeter of additional rainfall or irrigation water (0.18 to 0.30 tons of grain DM or 0.36 and 0.62 tons of silage DM from each acre per inch of rainfall). Moderate to severe water restriction has reduced yield of grain plus stover in a linear manner across various plant populations (Fig. 3; Soderlund et al., 2012).

Water requirements also vary within the growing season due to differences in rate of plant growth, plant size, and geographic region, all factors that alter the extent of evapotranspiration (ET). By definition ET is the process by which water stored in soil or vegetation is converted from liquid to a vapor and transferred to the atmosphere. The heat of vaporization associated with transition of liquid to vapor is drawn from the soil or vegetation and cools the surface temperature (Maes and Steppe, 2012). Plant growth and maturation is a function of “growing degree days.” This value is the seasonally summed mean daily temperature within the range of 10 (50°F) to 30°C (86°F). These extremes represent the minimum and maximum ambient temperatures across which plants accumulate dry matter when provided with adequate amounts of all needed nutrients including water.

**EVAPOTRANSPIRATION**

Water use by field crops and ET estimates typically are based on a vertical measurement of supply (similar to rainfall) independent of land area. Maize plants lose an equivalent of between 2.5 to 9 mm water daily to their environment in the U.S. Midwest (Fig. 4; Kranz et al., 2008). Peak ET occurs at the V12 to R1 (late vegetative and early reproductive) stages of maize plant development. High solar radiation, high air temperature, air movement, and low humidity will increase ET whereas cloudy, cool, and calm days will decrease ET. In contrast to cooling by ET, plant surface temperatures increase as wind speed and relative humidity decrease (Maes and Steppe, 2012), so ET is not strictly proportional to surface temperature. Nevertheless, in areas where temperatures are sufficient for plant growth, planting the crop early in the season or selection of shorter season hybrids, through avoiding the hottest, driest time of the year in much of the United States, will reduce ET and the need for supplemental irrigation. Season length, soil fertility and type, water availability, and their interactions also alter ET. Within the United States, ET for the total growing season for maize will range from about 600 mm in more humid areas to over 700 mm in arid regions (24 to 28 inches).

Plant responses to drought differ not only with the degree of water restriction but also with the timing and duration of water restriction. Matching the ET curve (Fig. 4), water restriction has its greatest negative impact on grain yield through reducing the kernel number during the plant’s reproductive stage near pollination. Maize grain yields generally are correlated more closely with kernel number per plant rather than with weight per kernel (Bolanos and Edmeades, 1996). Consequently, drought that reduces grain set has a greater impact on grain yield than drought at other growth stages. Water
restriction at earlier plant growth stages will reduce silage yields by reducing plant size and height and photosynthetic capacity. Restriction after pollination will reduce grain fill (reducing grain yield and starch content of silage) and can result in kernel abortion.

HYBRID SELECTION
FOR DROUGHT TOLERANCE

Maize hybrids are marketed primarily to plant growers whose first interest is maximum yield of grain or silage, although minimum risk and expense for crop production are additional concerns for maize growers. Based on these primary interests of plant growers who purchase seed, the plant breeders involved with hybrid development and selection for commercial companies select hybrids first for yield and secondarily for greater resistance to disease and insects and increased tolerance to herbicides and nutrient and water deficiencies. For acceptance across years as well as across a broad geographic area, a drought-tolerant hybrid must not only retain a substantial proportion of its potential yield under drought conditions but also have a high yield potential when the supply of water is adequate.

Drought tolerance typically is measured as the degree that yield of silage or grain is reduced when the amount of irrigation is restricted below ET or when the timing of irrigation is altered. For strictly controlling the supply of available water, drought tolerance trials are conducted in geographic regions where rainfall is either marginal (Colorado, Kansas, and Texas) or extremely limited (California and Chili) so that the amount of irrigation water or its timing can be closely controlled, preferably with subsurface drip tape. Such test sites allow plant breeders to observe agronomic characteristic of individual hybrids under various watering regimes ranging from severe drought stress to full irrigation. By plotting the yield ranking following water restriction against the yield ranking when adequate water is supplied, a simple graphic can be prepared for comparing the drought tolerance of various hybrids. Hybrids with greater drought tolerance should prove useful not only to reduce the need for irrigation water where irrigation is practiced routinely but also in nonirrigated regions where intermittent drought often occurs (DuPont Pioneer, 2011).

The 2 primary factors involved with drought tolerance of plants are an adequate root system to reach and retrieve available moisture from soil and minimal ET loss. Evapotranspiration can be reduced by decreasing exposure (restricting leaf dimensions or altering leaf angles) or by decreasing transpiration per unit of leaf area, as illustrated by Maes and Steppe (2012) and Lawlor (2013). These targets have led to various molecular and physiological approaches to increase drought tolerance (Bruce et al., 2002). Phenotypic differences observed for hybrids with higher drought tolerance scores become readily apparent in drought tolerance studies. Tolerant hybrids exhibit less leaf rolling, a greater “stay-green” characteristic, less leaf firing, and greater kernel fill, particularly at the ear tips (countering the Spock syndrome). Numerous gene markers associated with greater drought tolerance have been located. Compared with hybrids that are less tolerant of drought, those with greater drought tolerance maintain a greater photosynthetic rate under water stress but also have less stomatal conductance that serves to decrease ET when the water supply is restricted. When drought stressed, numerous alterations in gene transcription and in proteins involved with osmoprotection occur. Through modifying those genes involved with these responses, genetic engineering has the potential to enhance drought tolerance (Yang et al., 2010). However, the impact of changing certain metabolic pathways and products associated with increased drought tolerance of plants (e.g., greater proline and lignin content) deserve further research attention by livestock nutritionists.

To examine the genetic change in water use efficiency (kg grain/cm water) among hybrids grown in the past, maize seed stored from 3 elite Pioneer brand hybrids that were widely marketed each decade since 1920 were used. These hybrids were grown under managed drought stress or at 100% ET (304 vs. 762 mm irrigation) in Woodland, CA, in 2011 (Edmeades, 2013). Hybrids marketed within the past 30 yr yielded from 68 to 80 kg DM of grain per cm of water, nearly triple that of the hybrids marketed between 1920 and 1950. Similarly, Yu and Babcock (2010) concluded that the loss in maize grain yield from drought of a given severity is less today than was true in the past. Although a portion of this improvement in water use efficiency can be attributed to greater productivity of modern hybrids, a portion likely is due, albeit unintentionally, to hybrid selection. Intermittent drought occurs naturally within the regional field test plots where plant breeders grow their hybrids to select, advance, and market. As a result of reduced yield in those nonirrigated plots during years with partial or intermittent drought, hybrids automatically have been selected for greater drought tolerance. Much of the increase in maize grain yield in past decades can be attributed to the greater plant populations being grown associated with an increased tolerance of selected hybrids to various stresses, including water stress, associated with high plant populations. Hence, selection under high population stresses also appears to enhance selection for drought tolerance (Lopes et al., 2011). Hybrids selected for and marketed as drought-tolerant hybrids have shown consistent yield advantages in widespread field tests even when supply of water has not been restricted (DuPont Pioneer, 2014). This presumably implies either
that water shortages have occurred at some point during the growing season even when growing conditions appeared favorable or that plants with lower ET, by sparing soil moisture early in the growing season, conserve soil water that can be used later in the growing season to maintain plant growth and grain production.

Within the past decade, conventional breeding approaches for drought tolerance have been supplemented with molecular breeding procedures. Genetic trees as well as genotyping of the maize plant have speeded selection of hybrids with specific physiological characteristics (e.g., deeper roots, stomatal restrictions, and other factors that reduce ET [Miller, 1916]) apparent in drought-tolerant plants. Proprietary transgenic programs to develop plants with genes that will increase water storage within the plant (e.g., cacti) or allow plants to become temporarily dormant during drought (e.g., sorghum) can be visualized. Hybrids with such traits, even if their yield potential is low, should prove useful in regions that experience drought every year. Yet because drought within a specific region currently cannot be prognosticated reliably by climatologists or almanac editors, a drought-tolerant hybrid that yields well during a season when adequate water is available would seem preferable for growers in the more temperate maize-growing areas of the world where rainfall is adequate most years.

WATER USE EFFICIENCY

Agricultural activities account for about 75% of total water consumption (UNEP, 2009). Although this water consumption estimate for agriculture presumably includes all the water input including rainfall that otherwise would have limited use, production of cereal grains in regions with marginal rainfall relies completely on irrigation and if an irrigation equivalent to 700 mm rainfall is needed for maximum maize grain production, the total land area currently producing maize grain in the world (i.e., 5.2 × 10^11 m^3) was used for irrigation and if an irrigation equivalent to 700 mm rainfall is needed for maximum maize grain production, the total land area currently producing maize grain in the United States (i.e., 3.9 × 10^11 m^2) could be nearly tripled if this water was used to irrigate maize. Nevertheless, efficiency of water use should be maximized and water waste should be reduced wherever possible.

Water use efficiency is defined as the ratio of output (e.g., amount of grain, of plant DM, or projected milk yield from silage) per unit of water input (i.e., irrigation plus rainfall). Water use efficiency for silage production and for milk production was evaluated from 1 maize drought experiment (Soderlund et al., 2012). Water was provided at 100, 50, and 25% of ET throughout the full growing season for 109 to 114 comparative relative maturity (days from planting to full dent maturity of grain) Pioneer brand hybrids. This experiment was performed at a managed drought stress test site in La Salle, CO, in 2010 with plants at 3 population densities (59,000, 89,000, and 119,000 plants/ha [24,000, 36,000, and 48,000 plants/acre]). Counting rainfall, water supply for restricted plants was reduced by 38 and 57%. These restrictions reduced silage yield by 36 and 52% (Fig. 3), starch content of plant DM by 13 and 39% (data not shown), and projected milk production per hectare from maize silage by 26 and 53% (Fig. 5), respectively (Shaver et al., 2006). In contrast to these reductions in yield, water use efficiency for production of plant DM actually was improved by restriction. Compared with plants at 100% ET, water use efficiency for production of plant DM averaged 18% more at 50% ET and 13% more at 25% ET (Fig. 6). Similar improvements in water use efficiency for predicted milk production per hectare were noted (19 and 11%; Fig. 7). If 100% ET was an overestimate of actual ET, water restriction would be expected to increase efficiency of water use. Yet plant growers would need to sacrifice silage yield by 36% and milk per hectare by 53% to increase water use efficiency by only 19%. Consequently, maximizing water use efficiency seems counterproductive. Indeed, the linear responses in plant and milk production to added water (Fig. 3) imply that water restriction proportionally reduced plant yield. Therefore, maximum water use efficiency seems untenable as a target when developing hybrids or enacting legislation to conserve water. Effects on water use efficiency must be balanced against the impact of water restriction on crop production and sustainability. Certainly, maximum efficiency of water use is not congruent with maximum caloric or economic return per unit of land, particularly in regions of the world where the availability of arable land.
rather than availability of water limits the supply of food available for animals and humans.

Whenever water supply exceeds immediate needs, crop and soil management practices to conserve moisture in soil (e.g., no-till practices, avoiding soil compaction that increases runoff) and to reduce loss of excess water should be used. With rain-fed maize production, loss of soil, nitrate, and phosphorus in the runoff water can be substantial. These losses in runoff water are avoided when maize is irrigated. Thus, despite its dependence on an external source of water, irrigation has advantages over rain-fed crop production in terms not only of increased productivity and yield consistency but also in terms of a reduction in environmental costs related to wastes involved with runoff of both nutrients (nitrate and phosphorus) and soil. Irrigated maize production also is more amenable than dryland production to technological and engineering advances that can reduce water and nutrient use (e.g., applying fertilizer via water only to specific regions within an irrigated circle of maize).

Where irrigation is essential for maize production, crop growers generally are less concerned about the amount of water being used than about plant productivity and return on their investments in land and irrigation. Therefore, those who practice crop irrigation are not compelled to reduce their use of water unless either the cost of water is high or enacted legislation restricts the supply of water (Service, 2009). Advanced on-farm water management decision tools, such as soil- or plant-moisture sensing devices, irrigation-scheduling equipment, or computer-based crop-growth simulation models, currently are used on 10% of farms with irrigation (Schaible and Aillery, 2012). Despite the availability of such technologies, this report estimated that over one-half of the irrigated area in the United States still is being irrigated with traditional, inefficient systems.

By regulating the timing and amount of water strategically, the quantity of water used for irrigation can be markedly reduced. Greater adoption of such technology is needed to meet the water conservation desires of both crop growers and the general public. Although alternative drought-tolerant crops can reduce the quantity of irrigation water needed and may displace maize in certain regions, drought-tolerant maize would be expected to have its greatest impact on avoiding yield losses in the regions where drought is intermittent and infrequent.

**IMPACT OF DROUGHT ON YIELD AND POTENTIAL MILK PRODUCTION**

Dry matter and starch yield and the percentage of grain (i.e., ratio of dry grain weight to dry plant weight) increase during grain fill and plateau at the kernel black layer stage (i.e., kernel maturity). Total plant dry weight and grain weight per unit of land area usually are greater with longer than with shorter season hybrids; plant stature is reduced when water supply is restricted (Soderlund et al., 2012). When water supply is limited, shorter season hybrids as well as lower plant populations often will help to maintain silage yield despite a decrease in grain yield (Allen, 2012). Shorter season hybrids often pollinate earlier in the season when environmental temperatures are lower. Similarly, by maturating within a shorter time span, shorter season hybrids have a lower seasonal ET.

In addition to its impact on plant yield, drought stress can alter the nutritive value of maize silage or maize grain. Drought during grain fill will decrease grain density (i.e., test weight) that, in turn, will result in discounts in grade
Drought-tolerant maize and price associated with an increased tendency for kernels to fracture during grain handling. Drought has been reported to depress the feeding value of maize silage per metric ton for growing steers in some years but not in others (Krause et al., 1980) perhaps because the stage of plant development will alter drought’s effects on plant stature and grain content. Drought stress consistently reduces the grain content of silage. Lacking the grain as a sugar sink, sucrose accumulates in vegetative tissues at levels greater than normal, CP content increases, and NDF decreases for most plant parts (Fernandez-Rivera and Klopfenstein, 1989) while the amount of N soluble in 80% ethanol (i.e., prolamins) in grain increases (Loomis, 1937). Because the sink for N is reduced with drought stress, nitrate accumulates in vegetative tissues; this increases the likelihood of nitrate (i.e., nitrite) toxicity for ruminants (Al-Kaisi et al., 2013). In contrast, drought stress consistently has increased in vitro NDF digestibility of maize plants by 0.5 to 1.5 percentage points.

Generally, yields of both silage and grain have been less among brown midrib (BMR) maize hybrids than non-BMR isogenic hybrids. The BMR hybrids, with less lignin than conventional corn hybrids, have NDF that is more rapidly fermented in the rumen; this allows feed intake and milk production of lactating cows to increase. Susceptibility to water stress has been greater for BMR hybrids (Fig. 3) leading to a lower water use efficiency (Fig. 6) and resulting in greater yield reductions from drought with BMR than with conventional hybrids. Nevertheless, NDF digestibility often is 4 to 7 units greater for BMR than non-BMR hybrids with or without drought stress. The concept that NDF digestibility may be associated with susceptibility to drought deserves further attention. In 1 study, drought tolerance of inbred maize plants was found to be correlated positively with their capacity to accumulate lignin in leaves (Xu et al., 2007) and possibly other tissues; drought-tolerant plants often have greater lignification of vascular tissues. Metabolic signals in Arabidopsis (a common plant model for maize) and in soybeans that initiate increases in lignin content of tissues and enhanced drought tolerance were isolated recently (Okamoto et al., 2013). Consequently, the nutritional impacts of drought and of drought tolerance on lignin structure, location, and NDF digestibility need further study.

**ECONOMICS OF IRRIGATION**

The cost for irrigation water in the United States currently ranges from $10 to $23/1,000 m$^3$ (Wichelns, 2010). The cost for water and its delivery at $23/1,000 m^3$ to meet an ET of 700 mm would be $189/ha. Based on the amount of irrigation water plus rainfall in the experiment by Soderlund et al. (2012), excluding the cost of installation and equipment for irrigation, cost of water delivered at 25, 50, and 100% of ET would have been $81, $117, and $189/ha. These costs can be compared with the value of maize silage produced per hectare at the 3 irrigation rates if one considers the value of maize silage to be $0.20/kg ($0.091/lb.) of grain present. The cost of water to increase silage yield is dwarfed by the increased value of the silage (Fig. 8) or of grain produced. So based on current economics, a massive increase in the price of irrigation water or in its taxation would be needed before production economics would decrease the amount of water used for irrigation.

Where the availability of water is restricted legislatively, crop farmers dependent on irrigation who plan to continue to produce maize grain or silage will need to either restrict their cropped hectares to maintain an adequate water supply to their irrigated hectares and retire some hectares or maintain hectares and reduce the supply of water to those hectares. More drought-tolerant crops, including sorghum and wheat, could be grown on the retired hectares. For maize, water application can be timed strategically to reduce the amount of irrigation water used; providing irrigation to meet ET losses during the reproductive stage of development appears most critical for maintaining grain yield. For maintaining silage yield, applying additional water before the reproductive stage may be preferable to increase DM yield, but for maintaining grain yield, increased irrigation during the later grain filling stage likely would generate greater economic return. Other agronomic and management alterations could involve the use of shorter season hybrids and seeding at times to reduce hot weather during plant growth, especially during pollination.
MANAGEMENT FACTORS THAT DECREASE WATER USE

Improved tillage practices, including no-till and strip tilling, by reducing evaporation from the soil surface decrease the need for supplemental water and increase water reserves in soil for plant use in the future. Control of weeds by conventional means or simplified by development of herbicide-tolerant hybrids reduces the competition with weeds for water. Insect control above ground helps reduce tissue damage and tissue moisture loss by plants. Control of rootworms and insects by hybrids engineered with Bacillus thuringiensis (Bt) genes help protect roots from physical damage and shortening, and precision planting for uniform and deep soil penetration by roots can increase the amount of soil moisture accessible to plants. Improved irrigation methods that can reduce evaporation (e.g., drop nozzles, ignoring circle corners, subsurface irrigation), proper timing of irrigation to reduce evaporative water losses, and precision farming tools that allow growers to apply appropriate amounts of water and fertilizer for the soil type within and across fields also can reduce input costs. Because yield potential and enhanced stress tolerance are 2 traits that appear to be closely associated (Lopes et al., 2011), selection of maize hybrids for both stress and drought tolerance would be expected to improve future plant use.

SUMMARY AND CONCLUSIONS

Drought-tolerant maize hybrids, selected by phenotypic and marker-assisted selection, have an enhanced root system for water extraction from soil and reduced evapotranspiration by plants. Effects of water restriction on yield vary with timing; grain yield is depressed by drought most during and after pollination but silage and biomass yield also are depressed by drought earlier during vegetative growth. Although efficiency of water use, measured as dry matter or potential milk yield from silage per unit of available water, may increase with slight degree of water restriction, grain and silage yields per unit of arable land decline linearly with water restriction. Selecting shorter season maize hybrids and planting earlier, through avoiding evapotranspiration during midsummer heat, can reduce the need for water from either rainfall or irrigation. Agronomic practices (e.g., altered seeding rates; modified tillage and irrigation practices) combined with drought-tolerant hybrids can help maintain production of grain and forage when the supply of water is limited.


