VARIATION AMONG GRAIN SORGHUM GENOTYPES IN RESPONSE TO NITROGEN FERTILIZER

by

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Abstract

Grain sorghum [*Sorghum bicolor* (L.) Moench] is an important crop in the semi-arid regions of Africa, Asia and United States. Productivity of grain sorghum is limited by soil fertility, especially nitrogen (N). Sorghum genotypes are known to vary in their response to nitrogen, however, the information on nitrogen use efficiency (NUE) is limited. The objectives of this research were to (a) determine the response of sorghum genotypes (hybrids and inbred lines) to nitrogen fertilizer (b) quantify genotypic differences in NUE; and (c) determine physiological and morphological basis of NUE. Field experiments were conducted at three locations in Kansas (Hays, Ottawa and Manhattan) during 2010 and 2011. Six hybrids and six inbred lines of grain sorghum were grown with 0, 45 and 90 kg N ha^{-1}.The experimental design was a split-plot design with N regimes as main plots and genotypes as sub-plot, with four replications. Planting was done in May and June across all the locations, and nitrogen fertilizer (Urea, 46% N) was applied at emergence. Data on N concentration in the leaves, stems and grain were determined. NUE and components of N use were computed for Ottawa and Manhattan as follows: Nitrogen use efficiency (NUE): Grain weight / N supplied; Nitrogen utilization efficiency: Grain weight / N total in plant; Nitrogen uptake efficiency: N total in plant / N supplied; Percent fertilizer recovery = [uptake (fertilized plot) – N uptake (un- fertilized plot)] / [N applied] x 100; and Nitrogen harvest index (NHI) = Grain N / N total in plant. Where N supplied = Rate of N fertilizer applied + soil N supplied. Growth and yield data were collected at all locations. There were significant effects of genotypes ($P < 0.05$) and nitrogen ($P < 0.05$) on biomass and grain yield across all locations.

Performance of hybrids was generally superior to the inbred lines of all traits. Sorghum hybrids 26506 and 99480 produced maximum grain yield across all locations. While inbred lines B35 and SC35 had the lowest grain yield. Maximum biomass and grain yield was obtained at 90 kg N ha^{-1}, followed 45 kg N ha^{-1}, and lowest in 0 N kg ha^{-1}. There were significant differences among genotypes for all NUE traits at Ottawa and Manhattan. Across genotypes, total NUE ranged from 17.2 to 42.6 kg kg^{-1}, utilization efficiency from 24.3 to 60.2 kg $kg^{-1,}$ N uptake efficiency ranged from 56.1 to 82.5%, recovery from 2 to 52%, and NHI from 43.6 to 81.3%. Among the genotypes, 99480 and 26506 both known to be post–flowering drought tolerance were high in NUE and component of N use. While genotypes B35 and SC35 were the lowest in NUE and components of N use. Overall, our data suggest that there were significant differences for NUE traits in sorghum hybrids and inbred lines. There are opportunities to breed for higher NUE in grain sorghum.

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Dedication

To My Parents

Chapter 1 - Literature Review

1. 1 Introduction and Justification

Nitrogen (N) is very transitory in the soil, because it is susceptible to leaching, denitrification, and volatilization. Over use of N can lead to pollution of water streams. The use of N is increasing and it is important to use it efficiently especially in Sub–Sahara Africa (SSA). The efficient use of applied and residual N should be considered more seriously in the overall nutrient management than any other plant nutrient because it reduce it negative impact to the environment. Sorghum genotypes differ in nutrient absorption and that need to be exploit for improving the crop. Hybrids that can exhibit superior yields at all levels of N especially at low N rates are necessary. As the prices of N fertilizer increases, it is reasonable to believe that, increasing number of farmers will use high nitrogen use efficiency (NUE) sorghum varieties to reduce the cost spent on N fertilizer as an input. Efficient N cultivars will increase the production of sorghum based cropping system since it is among the major crops adopted in cropping systems in West Africa.

Difference exists both between and within species to use mineral nutrients more efficiently for growth and development. While some genotypes are capable of performing well under nutrient stress conditions, while others will perform poorly. Genotypic differences for nutrient use especially NUE have been recognized. However, the mechanisms that explain how these genotypes are able to satisfy all their biosynthetic and maintenance needs, but use a smaller amount of nutrient than required by other genotypes is still not well studied (Maranville et al., 2002). An important step towards explaining N

use is identification and understanding of morphological, physiological and biochemical parameters associated with genotypes, which differ in NUE, both in terms of nitrogen uptake and nitrogen utilization efficiency (Maranville and Madharan 2002).

Despite the fact that some work have been done in trying to evaluate genotypes or hybrids and soil fertility interactions, there is still no clear understanding of the physiological and morphological parameters associated with the efficient use of N. Plant growth and development are controlled by both inherent genetic and environmental factors, thereby leading to the degree of expression of genetic capabilities. Since environmental factors are not easily controlled, the understanding of physiological and morphological parameters associated with uptake, assimilation, translocation and deposition of N and dry matter in grain sorghum might prove valuable criteria in the selection of hybrids that are more efficient in extraction and utilization of nutrients.

1. 2 Production and Importance of Sorghum in Africa and US

Sorghum (*Sorghum bicolor* L. Moench) is a native to Africa, a region generally characterized by unpredictable rainfall pattern. The genus *Sorghum* is very diverse and all cultivated sorghums belong to *Sorghum bicolor* ssp. *bicolor,* which is divided, based on morphology, into five races (bicolor, caudatum, guinea, durra, and kafir), along with the ten intermediate races resulting from all possible inter–races crosses (Harlan and de Wet, 1972). The race bicolor is found nearly everywhere sorghum is grown and is characterized by very loose, open panicles similar to wild sorghum. Caudatum originated mostly from the region around Lake Chad to the Ethiopian border, while Guinea has its origins in West Africa and India and is grown in areas with higher rainfall. The Kafir race

is primarily from southern Africa while Durra has its origins around the edges of the Sahara and in India.

Grain sorghum is a major crop worldwide because of its adaptation to a wide spectrum of climatic and soil–fertility regimes. A drought tolerance characteristic of sorghum allows it to be grown in dry regions where summer temperatures are high and low rainfall prevent economical production of less tolerant crops. Today sorghum is cultivated across the world in the warmer climatic areas. It is quantitatively the world's fifth largest most important cereal after wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.) and barley (*Hordeum vulgare* L.). It is essential diet of poor people in the semi arid tropic where drought cause frequent failures of other crops. United States is the number one producer and exporter of grain sorghum in the world. In 2010, it produced 8,773,000 MT, while in 2011 the figured dropped to 6,246,000 MT. The total area planted to grain sorghum in 2010 was 13,510,000 ha, while in 2011, it was 13,667,500 ha^{-1} (USDA−NASS, 2011).

Average yields in Kansas ranged from 2700 – 5080 kg ha^{-1} within the last five years (USDA–NASS, 2011). This implies yields vary from year to year. In U.S, Kansas is the largest producer of grain sorghum. Grain sorghum is well suited to the dry arid climate of the U.S. Grain sorghum is a very important crop both in the economy and cropping system in the U.S especially in Kansas. Sorghum is the most drought tolerant summer crops grown in the central great plain regions. It has been estimated that about 1.2 million hectare of sorghum are currently cultivated each year by farmers in Kansas.

In Kansas it has been reported that, majority of grain sorghum cultivated is grown under dry land conditions. In the US, 90% of grain sorghum is primarily used as feed

stock for livestock industry (USDA−NASS, 2010). In recent years, sorghum is also used in ethanol and bio–fuel production, industrial manufacturing and as alternative food sources.

Grain sorghum plays an important role as a staple food grain in many developing countries in Africa. In Ghana, sorghum grain yield from farmer's fields is estimated at 0.8 tons per hectare (Buah and Mwinkara, 2009). In 2010 and 2011, Ghana produced 360,000 MT and 235,000 MT of grain sorghum respectively (USDA−NASS, 2011). Of late sorghum has gained some prominence among the breweries in Ghana. Government of Ghana in 2003 facilitated production of "Kapala"(ICSV III), pure–line cultivar in Northern Ghana to feed the country's breweries under the President's Special Initiative aimed at creating employment and reducing poverty in the area (GNA, 2003). In Ghana, grain sorghum is second to maize as a cereal grain and is used both as human food and as animal feed. However, in some communities the grain is also use for brewing alcoholic beverages, while the stems and foliage are often use for animal feed, fuel wood or as building material.

In the last three decades, per capita cereal production in West Africa has decreased from 150 to 135 kg person (FAO, 2010). The current annual growth rate of cereal production is very low at 1%, which is not able to meet the demand of population growing at a rate of 3% (UN, 2003). The annual credit deficit in sub–Saharan Africa is very high and the food gap (food requirement minus production) is widening. Thus, there is an urgent need to increase the productivity of food crops in West Africa. The per capita decline in crop productivity in West Africa is due mainly to limiting water (erratic rainfall and drought) and nutrient replenishment (soil fertility management and

deterioration of soil quality) and weed infestation. Increasing need for food and feedstock as a result of increasing population is leading to cultivation of crops on marginal lands with low fertility and poor soil quality. In West Africa, removal of crop residues from the fields, coupled with lower rates of N fertilizer (macronutrient) application compared to nutrients losses (crop mining), has contributed to negative nutrient balance. For example, in sub–Sahara Africa, 4.4 million tons of N is lost per year, and only 0.8 million tons of N is applied back into soil (Bationo, 2004). Considering the importance of soil moisture for crop growth and for the uptake of the plant nutrients in the rooting zone, the effectiveness of soil fertility enhancing measures should be related to rainfall regimes and or micro–management of water and nutrients.

The problems in West Africa are similar to those in Kansas, as summer crops soybean (*Glycine max* L. Merr) and sorghum in Kansas often experience drought and heat stress. At the present trend of changes in climate, the role of dry land agriculture and deficit or limited irrigation and optimal use of nutrients and resources will be more critical. In Kansas, sorghum has great potential to substitute maize and soybean due to its greater tolerance to drought and heat. Furthermore, the water use efficiency of sorghum is greater than maize and soybean and can out performed both in dry years (Gardner et al., 1994). There is greater potential for sorghum production under rain–fed conditions if we can improve water and nutrient use efficiency of sorghum. Furthermore, due to the recent drive for ethanol production, sorghum would be a well–suited crop due to its local importance and greater tolerance to environmental stresses.

Adaptation of sorghum to a wide range of environmental conditions in the sub−Saharan regions has resulted in the evolution of extensive genetic variation for

drought tolerance, low soil nutrients, making sorghum one of the most drought–tolerant cereal grain crops. Its rich and apparent genetic diversity for stress tolerance makes it an excellent crop model and choice for evaluating the genetic and physiological mechanisms of drought tolerance and nutrient efficiency. Direct selection for nutrient use efficiency using conventional approaches has been slow and difficult. Although a number of physiological and biochemical traits have been associated with the enhancement of nutrient use efficiency, only a few of these mechanisms have been demonstrated to be causally related to the expression of NUE under field conditions (Maranville et al., 1980). It is therefore important to understand more of the physiological traits in grain sorghum as a basis for future improvement in terms of NUE. Some physiological traits that are associated with NUE include, greater photosynthesis rates, increased green leaf area duration (stay–green), high N concentration in the leaf and specific leaf area. It is a known fact that, early onset of senescence affects assimilation and grain filling. The rate of senescence determines the maintenance of seed fill duration and rate. Therefore, any defense mechanism that postpones the onset of senescence and keeps leaves green will benefit the crop. Thus, stay green trait becomes very important in NUE management strategies.

1. 3 Growth and Development of Grain Sorghum

In a publication entitled “How a Sorghum Plant Develops”, by Vanderlip (1993) grouped the stages of the development of sorghum into nine stages. These stages have some distinctive characteristics. Time required to reach each stage depends both on the hybrid and on the environment in which it is growing. Other factors such as soil fertility, insect or disease damage, moisture stress, plant population, and weed competition may

also affect both timing of the various stages of development and condition of the plants at each stage of development. Modern hybrids are insensitive to day length; hence, their rate of development is primarily driven by temperature. The growth stages of grain sorghum are explained below.

1. 3. 1 Stage 0

This is the emergence stage and it takes about 3 to 10 d after planting for grain sorghum seed to emerge from the soil. This process is influence by factors such as soil temperature, depth of planting, vigor of the seed and soil moisture conditions. During this period of growth, the plant is susceptible to stress such as diseases, example damping–off. When the field conditions are cool and wet especially on no–till fields, planting should be timed so that germination and early growth occurs during periods of warm temperature so that flowering will occur before the hottest period of summer.

1. 3. 2 Stage 1

This stage will normally occur about 10 d after emergence and plants are at the three–leaf stage. This is when the growing point is still below the soil surface. Leaves are usually counted when the collar of the leaf can be seen without tearing the plant part.

1. 3. 3 Stage 2

This is the five–leaf stage, which occurs about 21 d after emergence. At this stage, the root system develops very rapidly and this leads to roots been produced at the lower nodes. The plant enters its grand period of growth at this stage. Dry matter accumulates at nearly a constant rate until maturity if growing conditions are satisfactory. Weed

competition, nutrient and water stress as well as insect pest damage can seriously reduce yield if they are not corrected.

1. 3. 4 Stage 3

This is the stage known as the growing point differentiation. This is about 30 d after emergence. The growing point change from vegetative to reproductive during this stage. Growing point differentiation is the stage when the total number of leaves has already been determined and the potential head size will be determined soon during this growth stage. Thus, about one–third of the total leaf area will have been fully developed. The culm or stalk growth increases rapidly and nutrient uptake is rapid. It is estimated that the time from planting to growing point differentiation is about one–third of the time from planting to physiological maturity. Adequate supplies of nutrient and water are necessary to produce maximum growth at this stage, as growth and nutrient uptake is rapid.

1. 3. 5 Stage 4

Stage 4 is the period when the flag leaf is visible in the whorl. About 80 percent of the total leaf area will have been formed at this stage. Nutrient uptake and growth continue to be rapid and light interception is approaching maximum. The lower 2 to 5 leaves may have been lost at this stage and the head (panicle) starts to develop. While only about one–fifth of the total growth may have occurred, nutrient uptake is far greater with more than 40 percent of potassium already taken up.

1. 3. 6 Stage 5

Growth stage five is known as the boot stage. All the leaves are now fully expanded, providing maximum leaf area and light interception. The head could have been develop to nearly full size and enclosed in the flag leaf sheath. The culm elongation is completed and the peduncle elongation is beginning and will result in exsertion of the head from the flag leaf sheath. Potential head size has already been determined. Rapid growth and nutrient uptake are continuing and severe moisture stress will prevent the head from extending completely from the flag leaf sheath.

1. 3. 7 Stage 6

Half bloom period which is the stage when one–half of the plants in a field or area are in some stage of bloom. In sorghum flowering starts from the tip downwards over four to nine days. Half bloom of an individual plant is when the flowering has progressed half–way down the head and one–half of the total dry matter weight of the nutrient will have reach nearly 70, 60 and 80 percent of total N, P and K respectively. The maturity of a hybrid and environmental conditions influences the time from planting to half–bloom. Generally, it represents two–third of the time from planting to physiological maturity. Grain formation begins at this stage, hence growth limitation such as plant size, leaf area or plant numbers can no longer be corrected.

1. 3. 8 Stage 7

At the soft–dough stage, grain fill rapidly between the half bloom and soft–dough stage and half of its dry weight is accumulated at this stage. While culm weight increases during the half bloom, it losses weight during the soft dough stage as a loss in culm weight may account for as much as 10 percent of the grain weight.

1. 3. 9 Stage 8

During the hard–dough stage, about three–fourth of the grain dry weight will have been accumulated. Nutrient uptake is completed and the culm has declined to its lowest weight and additional leaves may have been lost.

1. 3. 10 Stage 9

This is the growth stage when maximum total dry weight of the plant has occurred. Physiological maturity can be determined by the dark spot on the opposite side of the kernel from the embryo. Variation with hybrid and environmental conditions influences the duration from time of flowering to maturity and it represent about one–third of the duration from planting. Grain moisture content varies with hybrid and growing conditions, however, it is between 25 – 35% moisture at this stage. After physiological maturity, the remaining functional leaves may stay green or die and brown rapidly. The culm or stalk weight may increase slightly near physiological maturity.

1. 4 Importance of Nitrogen to Sorghum Production

Nutrient availability to plants is composed of several processes in the soil–plant continuum before a nutrient is absorbed or utilized by a plant. These processes include application of nutrient to soil or nutrient existing in the soil, transport from soil to plant roots, absorption by plant roots, transport to plant tops, and finally, utilization by plant in producing economic parts or organs. All these processes are affected by climatic, soil, and plant factors and their interactions. These factors vary from region to region and even within the same region. Hence, availability of nutrients to plant is a very dynamic and complex process.

The use of N fertilizer varies among the developed and developing countries. FAO (2010) reported that in 2009/2010 Africa used 1,566,000 tons of N fertilizer and 1,776,000 tons in 2010/2011. However, US during the same period used 7,833,000 tons and 7,461,000 tons in 2010/2011. Nitrogen fertilizers are expensive inputs costing agriculture more than US$45 billion per year (Ladha et al., 2000). Inorganic fertilizer N has played an important role in increased crop production and consequently in feeding the growing world population. For instance, the green revolution which combined higher grain yield with increased use of chemical fertilizer enable much of Asia and Latin America to achieve agricultural self–sufficiency in the 1960s and 1970s (Mann, 1997). However, the green revolution has never been fully applied to some of the world's poorest areas including SSA. Sub–Sahara Africa agricultural production is characterized by eroded soils, deprivation, and lack of soil organic matter (Sanchez et al., 2002).

Globally, higher cereals yields especially of grain sorghum are likely to be achieved through a combination of increased N application in regions with low N fertilizer such as SSA and improved NUE in countries such as US where current fertilizer use is already high (Dobermann, 2004.). Nitrogen fertilization normally increases the yield of grains, fruits or forage of non–legume plants. An important effect of N is that it promotes vegetative growth. When N is applied in the correct amount, it produces a dark green, healthy plant that reaches maturity more rapidly than nitrogen deficient plants. However, N can occasionally delay crop maturity when applied in amount greater than the crop needs. The atmosphere contains a large, well–mixed, biological unavailable pool of N of which a relatively small part is converted to biological available or reactive pool of N. However, industrial N fixation has become equally important in agriculture, since

the growing demand for food has forced large increases in the use of N fertilizers. Nitrogen uptake occurs at a faster rate than dry matter accumulation. For instance, during the early growth stage following emergence, grain sorghum will take up no more than 5% of the total seasonal N needs. Nitrogen is vital to get seedlings off to a rapid start. About 60 d after planting until near maturity grain sorghum requires large amount of N each day.

Nitrogen is one of the most yield–limiting nutrients for crop production in the world. It is also the nutrient element applied in the largest quantity for most annual crops. Systems of agriculture that rely heavily on soil reserve to meet the N requirements of plants cannot long be effective in producing high yields of crops. In developing countries, intensive agricultural production systems have increased the use of N fertilizer in efforts to produce and sustain high crop yields (Fageria et al., 2003). Nitrogen has greater influence on growth and yield of crop plants than any of the essential plant nutrient. It plays a pivotal role in many physiological and biochemical processes in plants. Nitrogen is a component of many important organic compounds ranging from proteins to nucleic acids. It is a constituent of the chlorophyll molecule, which plays an important role in plant photosynthesis. Many enzymes are consists of protein cells; hence, N plays a key role in many metabolic reactions. Nitrogen is also a structural constituent of cell walls. Nitrogen–deficient plants grow slowly, and their leaves are small. Nitrogen deficiency also decreases leaf area index (LAI), lowers radiation use efficiency, and lowers photosynthesis activity in plants (Muchow, 1988; Sinclair and Horie, 1989; Fageria and Baligar, 2005). Stewart et al. (2005) reported that the average percentage of yield attributable to N fertilizer generally ranged from about 40 to 60% in the United States

and England and tended to be much higher in the tropics in the 20th century. Stewart et al. (2005) reported that omission of N in maize declined yield of this crop by 41 % and elimination of N in cotton production resulted in an estimated yield reduction of 37 % in the US. The contribution of chemical fertilizers especially N fertilizers has reached 50 to 60 % of the total increase in grain yields in China (Wang et al., 1995). The role of N nutrition in increasing crop yields in the 21th century will be higher still, because world population is increasing rapidly and it is projected that there will be more than 8 billion people by the year 2025. Limited natural resources like land and water and stagnation in crop yields globally make food security a major challenge and opportunity for agricultural scientists in the 21th century. It is projected that food supply on the presently cultivated land must be doubled in the next two decades to meet the food demand of the growing world population (FAO, 2004). To achieve food production at a desired level, use of N fertilizers, efficient hybrids in nutrient uptake and utilization and improvements in soil fertility are indispensable strategies.

1. 5 Definition and Concept of Nitrogen Use Efficiency

Worldwide nitrogen NUE for cereal production such as wheat, maize, rice, sorghum and pearl millet (*Pennisetum glaucum* L.) is approximately 33%. The unaccounted 67% represents about $15.9 billion annual loss of N fertilizer assuming fertilizer–soil equilibrium. Losses of N fertilizer results from soil denitrification, surface runoff, volatilization and leaching (William et al., 1999). Agriculture research previously was dominated by productivity. The environmental impact of the crops and cropping systems, the quality of the products, the lowering cost of production and increased NUE are among new areas of research interest. Understanding the processes that governs N

fluxes, particularly N uptake and distribution in plants is of major importance with respect to both environmental concerns and the quality of crop products. Efficiency in uptake and utilization of N in the production of grain requires those processes associated with absorption, translocation, assimilation and redistribution of N to operate effectively.

The relative contribution of genotypic or hybrids differences in NUE vary among genotypic populations and environments including N supply. Therefore, it is important to characterize efficiency of N use in terms related to variation in the major processes involved. The quantitative analysis of plant efficiency for N uptake and utilization is usually defined in terms of total yield per unit of N removed under a given set of environmental conditions. Plants which may be efficient for a certain element under limited supply may not be the most efficient when the element is supplied optimally.

In West African savannahs where sorghum is becoming important, inorganic fertilizer use is limited due to high cost and non–availability. To reduce the impact of N deficiency on sorghum production, the selection of hybrids and genotypes that are superior in the utilization of available N either due to enhanced uptake capacity or because of more efficient use of the absorbed N in grain production can be an option (Lafitte and Edmeaedes, 1994).

Various indices are mostly used in agronomic research to assess the efficiency of applied N as reported by (Cassman et al., 2002) and these are mainly for the purpose that emphasize on crop response to N. In the field studies these indices are either calculated based on differences in crop yield and total N uptake with above ground biomass between fertilized plots and on unfertilized control (difference method) or by using ^{15}N–labeled fertilizers to estimate crop and soil recovery applied N. The agronomic framework is

most useful for understanding the factors governing N uptake and fertilizer efficiency to compare short term NUE in different environment and to evaluate different N management strategies or technologies.

The difference method is simple and cost efficient which makes it suitable for on farm research (Doberman, 2005). On a global or regional scale, partial factor productivity of N (PFPN) is the only index of NUE that can be estimated reasonably well, although not very precisely because of uncertainties about the actual N use by different crops. Because PFPN is a ratio, it always declines from large values at small N application rates to smaller values at high N application rates. Thus, differences in the average cereal PFPN among world regions depend on which cereal crops are grown, their attainable yield potential, soil quality, amount and form of N application, and the overall timeliness and quality of other crop management operations (Doberman, 2005).

Nutrient efficiency definition varies greatly. For instance, Maranville et al. (1980) working on sorghum defined NUE as (1) biomass per unit of plant N (NUE1) (2) grain production per unit of plant N (NUE2) or (3) the product of NUE2 and the ratio of grain N content to stover N content (NUE3). Nitrogen use efficiency can also be defined as the maximum economic yield produced per unit of N applied, absorbed, utilized by the plant to produce grain and straw. Nitrogen use efficiency can be classified as agronomic efficiency, physiological efficiency, agro–physiological efficiency, apparent recovery efficiency and utilization efficiency (Fageria and Baligar, 2001; Santos et al., 2003).

Moll et al. (1982) defined NUE as the ratio of grain weight to N supply (Gw/Ns) and N supply as the amount of plant available N in the soil. Despite the importance of N in crop production, a clear understanding of the major mechanisms and inheritance of

NUE is lacking (Basra and Goyal, 2002). Part of this may be due to the inherent complexity of NUE as it is a function of multiple interacting genetic and environmental factors. The immediate goal of improving agricultural NUE is to improve the recovery of N from N fertilizer, either organic or synthetic. Globally, only one–third of the N in fertilizer applied to cereals crops is harvested in the grain (Raun and Johnson, 1999).

Several different strategies are currently been pursed to address problems associated with inefficient agricultural systems and the N cascade (Galloway et al., 2002). One of such method is breeding efforts that are married at the developing crops varieties and hybrids that are more efficient at capturing soil N and applied N, thereby decreasing N leaching and denitrification losses and reducing plant N requirements (Cassman et al., 2002). If plant have higher N uptake, there is less soluble N in the soil that could be immobilized or lost (Fiez et al., 1995). In field experiments, plant available N may be calculated as the total N in plant tissues plus the residual inorganic N within the root zone. It is also possible to measure the grain N accumulation efficiency, which is the amount of N in the grain divided by N supply (Ng/Ns). This serves as a measure of the overall efficiency with which plant extract N from the soil and accumulate it in the grain by harvest.

Another important additional parameter is the N harvest index (NHI). Nitrogen harvest index is the ratio of N present in grain to total plant content (Ng/Nt), analogue to harvest index which is the ratio of grain N content to total biomass. It is a measure of translocation efficiency. It is significant for maximizing grain protein content for a given amount of plant N. Thus, plant physiological components, N uptake efficiency and N utilization efficiency contribute to overall NUE. Nitrogen utilization (Gw/Nt), measures

the response of grain yield to total N in the plant, this can be done by measuring of the aboveground plant nitrogen. Nitrogen uptake efficiency was defined by (Moll et al., 1982) as the total aboveground plant N at harvest divided by the total N supply (Nt/Ns). Uptake efficiency is a measure of how much N the plant absorbs in proportion to the N supply (or plant available N). Plant N uptake is closely associated with assimilation, the incorporation of N compounds into plant tissues. This varies among and within crops such as grain sorghum. Reduction in NUE with increasing N supply could result from reduction in N uptake efficiency, N utilization efficiency and N retention efficiency. Studies have showed that on wheat and perennial grasses there was a reduction in all the three components (Cox et al., 1986; Dhugga and Waines, 1989; Jiang et al., 2001; Huggins and Paan, 2003).

The determination of NUE in crop plants is an important approach to evaluate the fate of applied chemical fertilizers and the role in improving crop yield. Nitrogen use efficiency is reported to be higher at lower N rates and decrease at higher N rates. This may indicates that plants are unable to absorb N when applied in excess because their absorption mechanism might have been saturated (Fagaria, 2003). Under this condition, there exist the probability that more N will be subject to loss through ammonia gas, leaching or denitrification.

Strategies to improve NUE in wheat have been studied by (Blankenau et al., 2002). These authors found that NUE could be improved if N available to the crop could be improved at critical growth stages. In wheat, this could be accomplished by modifying N application systems to lower N application at the growth stage when tillers begin to form and with higher N rates during later growth stages.

1. 6 Nitrogen Uptake, Partitioning and Dry Matter Production

Nitrogen is mainly absorbed as nitrate N and ammonium by roots. In oxidized soils, NO_3^- is the dominant form and absorption and this form predominates. In reduced soils conditions such as flooded fields with poor drainage, NH_4^+ may predominate in the absorption process. It has been proven that most annual crops grow best when supplied mixture of NO_3^- and NH_4^+ under controlled conditions (Goos et al., 1999). Among N–related traits, N uptake and its subsequent translocation to leaves appear to be critical to many plants. The value of agricultural experiments could be enhanced greatly if information on the dry matter production and partitioning are available (Royo and Blanco, 1999). This information will provide better analysis and interpretation of the results and, also allow one a better understanding of the processes and resources exploitation for crop production (Williams et al., 1996). High yielding grain sorghum varieties managed under identical N fertilizer regimes do not yield as well as maize, but take up more total N from the soil. These differences may be due to the fact that grain sorghum translocate much less of its N from vegetative tissues to grains. Thus, this leaves grain sorghum stover with about 50% more total N than maize stoves (Perry and Olson, 1975). Thus, there is the need to get hybrids which can accumulate relatively large quantities of N in the early stages of growth and translocate a larger portion of the accumulated N to the grain.

Dry matter is an important component for determining grains yields in field crops. Photosynthetic products produced by green plants are divided into roots, shoots and grains. A part remains in the shoots and a part is translocated to the roots and grains, this process can be referred as dry matter partitioning in plants. Crops growth rate depends on

the amount of radiations interception by the crop and the efficiency of conversion of the intercepted radiation into dry matter (Sinclair and Hoire, 1989). Hence, it is prudent to develop grains sorghum hybrids that can efficiently and effectively intercept radiation for subsequent conversion into dry matter.

Low N concentration in plant leaves which varies among plant genotypes including grain sorghum is a factor of reducing RUE and biomass productivity (Sinclair and Horier, 1989). Variation in dry matter yield in response to N may arise from difference in the amount of intercepted photosynthetically active radiation by the canopy, RUE and grain harvest index (Charles–Edwards, 1982). Dry matter production has significant association with grain yield of plants grown under relatively high heat environment (Reynolds et al., 1994). Thus, this holds strongly for crops grown in Kansas including grain sorghum.

Grain growth is supported by photosynthetic activities of the flag leaves and inflorescence and by translocation of stored photosynthetic products resources in the plant canopy, which varies among and with plant (Blum et al. 1994). It has been reported that dry matter accumulation in cereals prior to anthesis is an important source of photosynthetic products for grain growth, which especially have plants grown under hot and dry climatic conditions during grain filling (Papakosta and Garianas, 1991).

1. 7 Genotypic Variation Among Sorghum Hybrids on N Use

Research has showed that there is intraspecific and genetic variability in inorganic nutrition among crops. Nitrate accumulation is influenced by environmental conditions and plant growth stages. Accumulation increases with available soil N and with the severity of various growth limiting factors including drought, adverse temperature (heat

or frost) and poor light conditions. The mechanisms by which some genotypes achieve superior N efficiency are yet unknown. Quantitative differences in N nutrition among varieties or hybrids may occur by genetic control of N translocation through the xylem, the degree of N retention in tissues, N mobility in the phloem, the efficiency of N metabolic utilization, as well as other processes (Epstein and Arnold, 2005). Aside from effective nutrient redistribution, efficient genotypes may have lower nutrient requirements at functional sites because they concentrate the nutrient into metabolically active forms.

Genotypic difference in N uptake partitioning and NUE (unit dry matter per unit N in dry matter) has been reported for crops such as maize (Cassman et al., 2002; Roberts, 2008) and grain sorghum (Maraanville et al., 2002). Exploiting genotypic difference in N demand and efficiency has been proposed as possible alternatives for reducing the cost and reliance upon fertilizer N. For instance, wheat genotypes have been found to differ in total plant N and NHI, with genotypes exhibiting the greatest N accumulation at harvest produced higher grain yield and grain protein (Gaucer et al., 1992). In addition, (Singh and Arora, 2001) compared NUE for 20 wheat varieties and found NUE was higher in tall varieties for dry matter production while dwarf varieties had higher NUE for grain production. Thus, within the same crop, there have been some variations in NUE, an indication of genotypic variation among the same crop species.

Some works about the combination of morphological and physiological factors that contribute to improve NUE have been carried. Maranville and Madhavan (2002) reported that physiological process of carbohydrates partitioning and N metabolism are associated. Thus, hybrids with difference in grain yield potential may have differences in

N accumulation and NUE. Physiological processes which are related to N stress tolerance in terms of gas exchange rates and stomata conductance from a given supply of leave N have been studied (Pavlik, 1983; Field, 1983). Leaf morphological features can influence physiological processes and which could contribute to NUE (Longestreth and Nobel, 1980; Pavlik, 1983).

Genotypic variation in N utilization includes not only the quantity of N in the plant, but also, its distribution among plant parts. The relationship of growth to nutrient concentration in the plant depends on several interacting factors including distribution and mobility of the nutrients. Characteristics that correlate to NUE may provide clues to the mechanisms by which genotypes produces the same yield as other yet contains less N. The study of plant N efficiency will lead to increased understanding of plant N metabolism as well as, identification of characteristics that could be use to improve the N efficiency of hybrids used commercially.

1. 8 Hybrid Production in Africa

Generally, the area of sorghum in Africa has steadily increased over the years but the average yield trends are downwards. Paramount among the yield reducing factors are predominant cultivation of inherently low yielding varieties, poor soil fertility, drought, striga infestation, pests and diseases. Exploitation of host–plant resistance through genetic enhancement has always been the first approach or forms of an integrated control package in addressing these constraints. The various national agricultural research systems (NARS) either separately or in collaboration with international research centers such as International Crops Research Institute for the Semi–Arid Tropics (ICRISAT), Sorghum, Millet and other Grain Collaborative Research Support Program

(INTSORMIL)–CRSP of USAID and regional sorghum networks have drawn up research strategies to address the constraints facing the production and utilization and processing of sorghum. Although a lot of research on sorghum breeding has been carried out and documented within and without the continent of Africa, there is still a lot to be done looking at the current persistent constraints.

Between 1960s and the mid 1980s, sorghum hybrids were introduced into Niger, Mali, Nigeria and Burkina Faso. The West Africa hybrid Adaptation trial (WASHAT) from ICRISAT was also initiated in the mid 1980s and was conducted in about 17 countries in West Africa. In all these countries where sorghum hybrids have been compared to improve and landrace varieties, there has been a yield advantage. As growing conditions become stressed the yields of both decline, but the yield difference between hybrids and varieties become proportionately larger, favoring the hybrids. Out of the 17 sorghum growing countries in West and Central Africa, only Nigeria and Niger have formally released sorghum hybrids (Toure et al., 1998).

1. 9 Nutrient Stress in Africa and Ghana

More than 80% of the farmlands in SSA are plagued by severe land degradation, losing more nutrients annually than are being replaced. At the same time, farm yield per person in Africa has been declining over the last 40 years. Africa's crisis in food production and battle with hunger are largely rooted in a "soil health crisis," as vast swaths of farmlands are depleted of nutrients needed to grow crops. On average, African farmers annually apply one–fifth (< 10 kg) of the minimal amount of nutrients needed to maintain soil health, and fertilizer use is one–tenth the world average of 100 kg ha^{-1}. However fertilizer use in SSA is less than one–tenth of the world average eight kilograms

of nutrients per hectare. The region's share of world fertilizer consumption is less than 1 percent. Five countries account for 62.5% of this (South Africa, Nigeria, Zimbabwe, Ethiopia and Kenya). Nevertheless, even in these countries, fertilizer is most likely to be use with irrigated cash crops. It is simply beyond the reach of most smallholder farmers across SSA (Sanchez et al., 2002).

Farming without replacing lost nutrients leads to soil depletion, as nutrients are harvested along with each successive crop. Yields and crop quality decline, and soils are ultimately left barren. Negligible fertilizer use by smallholder farmers is a major factor in the region's declining farm yield per person, which has exacerbated hunger and under–nutrition on the continent. Shifting cultivation and fallowing have been the traditional method of maintaining soil fertility and replenishing nutrients in SSA (Blackie and Jones 1995; Blackie 1994). However, due to increased population pressure in most areas, fallowing has disappeared from the system in some areas and is declining in others. The shortening of fallow cycles without adequate replenishment of soil nutrients through the use of organic and inorganic inputs has caused yields to decline over time (Ehui et al., 1994; Eswaran et al. 1999). In general, soil fertility is on a downward spiral, with inputs of nutrients (from organic and inorganic sources) into sedentary agriculture insufficient to reverse the trend. Estimated rates of net nutrient depletion are high, exceeding 30 kg N ha^{-1} and 20 kg ha^{-1} of potassium (K) ha^{-1} of arable land per year in Ethiopia, Kenya, Malawi, Nigeria, Rwanda, and Zimbabwe (Stoorvogel et al., 1993). Stoorvogel (1990) reported that an average of 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} has been lost during the last 30 year from about 200 million ha of cultivated land in 37 African countries, excluding South Africa. This is equivalent to 1.4 ton urea ha^{-1}, 375 kg ha^{-1} of

triple superphosphate (TSP) or 896 kg KC1 ha^{-1} during the last three decades. These figures represent the balance between nutrient inputs as fertilizer, manure, atmospheric deposition, biological N_2 fixation (BNF), and sedimentation, and nutrient outputs as harvested products, crop residue removals, leaching, gaseous losses, surface runoff, and erosion. These values are the aggregate of a wide variety of land–use systems, crops, and agro ecological zones in each country.

From 1988 to 1990, fertilizer use in Ghana averaged about 11,000 tons of NPK but 90,000 tons of the same nutrients were removed by various crops. The implications for Ghana are clear thus, depletion of soil nutrients is becoming a serious constraint to soil fertility and crop productivity. Moreover, the level of depletion suggests that large amounts of nutrients were needed to maintain soil fertility (Blum et al., 1994). Almost all the crop balances in Ghana show a nutrient deficit, i.e. the difference between the quantities of plant nutrients applied and the quantities removed or lost (FAO, 2004). This represents a loss of potential yield and progressive soil impoverishment. During the 1970s, fertilizer consumption increased ten–fold with a peak of about 31,000 tons total nutrients in 1977. The FAO fertilizer program was very active in Ghana and this probably contributed to the increase. Declining soil fertility has been identified as one of the most significant constraints to increasing food production in SSA. This is true even in the highlands of eastern Africa (traditionally the region's most productive and fertile lands) due to human population pressure and intensification in land use (Waddington and Ransom, 1995). Adequate and timely applications of the essential nutrients such as N and P will not only increase yields, but will also provide relatively higher amounts of crop residues, which can be used as organic matter to improve soil health and prevent soil

degradation (Blum, 1991). Considerably more plant nutrients are being removed and lost than are being applied, with a consequent progressive impoverishment of soils. Traditional, soil exhausting cultivation practices are still used extensively (Gardner et al., 1994).

The magnitude of nutrient depletion in Africa's agricultural land is enormous. Africa is now losing 4.4 million tons N, 0.5 million tons P, and 3 million tons K every year from its cultivated land. These rates are several times higher than Africa's annual fertilizer consumption, excluding South Africa values of 0.8 million tons N, 0.26 million tons P, and 0.2 million tons (FAO, 2004). Commercial farms in the temperate region have averaged net positive nutrient balances in the order of 2,000 kg N ha^{-1}, 700 kg P ha^{-1}, and 1,000 kg K ha^{-1} during the last 30 years in about 300 million ha of cultivated land, sometimes resulting in groundwater and stream pollution (Sanchez, 2002). Nutrient depletion in Africa, therefore, contrasts sharply with nutrient accumulation in temperate regions.

Both climate and soils tend to be more contrasting in Africa than elsewhere. These are among the most critical environmental factors that determine the sustainability of an agricultural system. Africa soils tend to be particularly poor in nutrients that cannot be absorbed by crops. Although organic matter level is not inherently lower in the tropics and Africa than in the temperate zones, the turnover (decomposition) rate of organic matter is often higher. The efficiency of chemical fertilizers and the long–term sustainability of yields can often be increased by adding organic matter from internal nutrient sources (e.g., green manures and farmyard manures), by employing reduced tillage techniques, and by alley crops (Matlon, 1990; Borlaug and Dowswell, 1994).

Farm–level studies show that technologies, which employ green manure crops, composting, and animal manures to increase soil fertility in smallholder agriculture have largely been rejected because of the high labor demands and the variable quality of the product. There are also problems in producing the quantity of manures and composts needed to have a noticeable effect on soil fertility (Blackie 1994; Jones and Wendt, 1995). Ehui et al. (1994) report that the benefits in improved soil quality, fertility, and crop yields are limited by the low output response of inputs such as manure, crop residues, and animal power. These inputs are also insufficient to replace the major nutrients mined from the soil by crop production. Thus, future increases in food production must come primarily from higher yields per unit of land rather than from land expansion. Agricultural research must therefore continue to develop yield–enhancing production technologies targeted to specific agro–ecologies, especially on food crops. Hence, soil fertility research should receive high priority and research in both organic and inorganic sources of nutrients must be encouraged and strengthened.

1. 10 General Hypothesis and Objectives

We hypothesized that there are differences among grain sorghum hybrids and inbred lines in nitrogen uptake partitioning, NUE, growth and yield.

The objectives of this study were to:

(1) determine the response of sorghum genotypes (hybrids and inbred lines) to nitrogen fertilizer;

(2) quantify genotypic difference in nitrogen use efficiency (NUE); and

(3) determine physiological basis of increased in NUE.

Chapter 2 - Material and Methods

Field experiments were conducted at three locations in 2010 and at two locations in 2011 to evaluate the response of grain sorghum hybrids and inbred lines to varying nitrogen fertilizer levels. The locations used for the study were in Western Kansas Agricultural Research Center at Hays (2010), KS (38° 52′, 45″ N / 99°, 19′ 35″ W), on a Harney silt loam, East Central Experimental Field near Ottawa (2010 and 2011), (38° 32′, 16′ N / 95°, 15′ 15″ W) on a Woodson silt loam and in Riley county at Ashland Bottoms Research farm located south of Manhattan (2010 and 2011), KS (39° 15″, 15″ N / 90°, 40′ 19″ W). In Ashland Bottoms, the fields were located at Unit 1 (39° 08′, 35.3″ N / 96° 37′, 39.2″ W) which was irrigated only in 2010 on a Belvue silt loam soil and Unit 7 (39° 06′, 54.2″ N / 96° 38, 10.0″ W) which was rain fed for both years on a Reading silt loam soil.

Average maximum and minimum temperatures, precipitation and relative humidity during the growing season (May through to October) for the study areas are in Figures 1 through 8. In three of the locations, Hays, Ashland bottom Unit 1 and Unit 7, the experiments were implemented on conventional tillage; however, in Ottawa it was on no–till. The previous crop in Unit 1 and Hays was sorghum while in Unit 7 and Ottawa it was soybean and maize respectively for 2010. However, in 2010 the previous crop in Unit 1 was sorghum and soybean in Unit 7 and Ottawa.

2. 1 Soil Sampling and Analyses

Results of or/ soil analysis are provided in Table 1. At each location a composite soil

samples were taken from each replication from a depth of 15 cm. Sampling was done using a hand probe and samples consisted of 12 to 15 individual cores mixed to form individual composite samples. The soil was analyzed for pH, available P, exchangeable K, soil organic matter (SOM), sulfur and chloride. In addition, profile ammonium and nitrate was measured in soil collected at 60 cm. Soil physical properties such as sand, silt and clay were also determined for each replication of a depth of 15 cm in all the locations. Analyses were conducted by KSU soil testing laboratory using procedures described for the North Central Region NCRR Publication No. 221 (1998).

Mehlich 3 phosphorus was analyzed by HCl−ammonium fluoride extraction method. This extraction and the colorimetric assay are described on pp. 21−22 and pp. 24−25, respectively, of "Recommended Chemical Soil Test Procedures for the North Central Region" (Frank, K., Beegle, D., and Denning, J.). For extractable (plant available) potassium, ammonium acetate extraction method was used. Analysis was conducted by an inductively coupled plasma (ICP) spectrometer (Model 3110 Flame Atomic Absorption (AA) Spectrometer, Perkin Elmer Corp., Norwalk, CT, US). Besides, extractable cations (K and Na) were determined by ammonium acetate (1M, pH 7.0) method as described by Warncke, D.M. and Brown, J.R. A low−sodium filter paper was used. The analysis was done by an inductively coupled plasma (ICP) spectrometer, (Model 3110 Flame Atomic Absorption (AA) Spectrometer, Perkin Elmer Corp., Norwalk, CT, US). Besides, chloride was analyzed by calcium nitrate extraction method and colorimetric analysis in mercury thiocyanate method. The colorimetric assay was performed using an Alpkem RFA Methodology No. A303-S090.

2. 2 Experimental Design

The experiment was conducted in a split–plot arrangement in a randomized complete block design with four replications. Each plot dimension was 6.1 m long and 3.0 m wide (4 rows). The inside two rows were set aside for data collection to eliminate any border effects. Each replication was separated by 2 alleys to eliminate any N fertilizer border effect.

The test genotypes consisted of six (6) hybrids and six (6) inbred lines with varying genetic background with known drought tolerance characteristic (pre–flowering and post–flowering drought tolerance) (Table 2). Three different N regimes were used to evaluate the genotypes in the all environments; control (no inorganic nitrogen supply), half recommended rate (45 kg N ha^{-1}) and optimum rate (90 kg N ha^{-1}). The N regimes were assigned as main plots and the genotypes as sub–plots.

2. 3 Crop Management

The nitrogen fertilizer source was urea (46% N). The fertilizer was hand broadcast 10 d to 14 d after emergence along the rows of each plot to ensure that N was evenly distributed. Standard spacing for sorghum, 75 cm between rows was used during planting at all the locations. Planting was done in May and June across all the locations. Weeds were controlled with pre–emergence herbicides applied at labeled rates using a tractor mounted boom sprayer. At Manhattan (Unit 1), Callisto at 0.37 L ha^{-1} and Bicep at 2.75 L ha^{-1} was used. Similarly, at Manhattan (Unit 7), Lumax 2.84 at the rate of 2.9 L ha^{-1} and Bicep at 3.3 L ha^{-1} was sprayed. However, at Ottawa, Atrazine at the rate of 1.1 L ha^{-1} and 2, 4-D at 1.1 L ha^{-1} was applied. While at Hays, Atrazine and Parallel were used at the rate of 2.4 L ha^{-1} and 1.8 L ha^{-1} respectively. Hand weeding was also done as

and when necessary throughout the growing season to reduce weed pressure. Plots were mechanically harvested after physiological maturity using a two row plot combine with which grain samples were collected to determine moisture content and test weight. Yields at all locations were then corrected to 135 g kg^{-1} moisture content. Important cultural practices related to the experiments are given in Table 3.

2. 4 Observations and Growth Measurements

Above ground portion of ten plants from each plot were randomly sampled at growth stage 3 (growing point differentiation), growth stage 6 (half bloom) and growth stage 9 (physiological maturity) as described by (Vanderlip, 1993).

At each sampling, the leaves were separated from the stems. In addition, at physiological maturity panicles were also removed separately. All samples were dried at 60°C in a forced air oven for 72 h and weighed. Based on the individual plot plant population, total biomass at the different stages were determined and expressed as kg ha^{-1}. The dried samples, leaves and stems were ground in a Thomas–Wiley laboratory mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA, US) to pass through 2.0 mm screen. The panicles were threshed in a stationary thresher (Model LDB, ALAMACO, Nevada, US) and the grain ground in a cyclone sample mill (Model 3010–030, Udy corporation, Fort Collins, Colorado, US). Leaves, stems and grains N were determined by digesting the samples using a sulfuric acid–hydrogen peroxide digest. The extract containing ammonia was analyzed by a colorimetric procedure (nitropruside–sodium hypochlorite) using RFA methodology no. A303–5072. The total N from the leaves, stems and grain was used to calculate nitrogen use efficiency, uptake efficiency and utilization efficiency according to the methods described by (Moll et al., 1982) for

Manhattan and Ottawa. Harvest index was calculated by dividing grain yield by total biomass produced (stover + grain).

At all the locations, five plants were tagged in the two middle rows for phenological measurement (days to 50% flowering and days to physiological maturity), growth traits (plant height, number of green leaves, total number of leaves and percentage leaves senescence at physiological maturity), physiological measurements (leaf chlorophyll content and chlorophyll *a* fluorescence) and yield and yield components (grain yield, harvest index, 200 kernel weight and kernel number m^{-2}). Plant height was recorded from the tagged plants at maturity by measuring the height from the ground to the tip of the panicle. Besides, percent leaf senescence was calculated as the percentage of the difference between total number of leaves produced per plant and number of green leaves at any particular time, expressed over the total number of leaves produced per plant.

Physiological measurement such as chlorophyll content of the leaves was measured with the aid of a soil plant analysis development (SPAD) 502 chlorophyll meter (Minolta Corp. Tokyo, Japan). Readings were taken at growth stage 3 from the uppermost fully expanded leaves from 5 different plants in each plot and averaged to one value per plot. At growth stages, six and nine the flag leaves were used for measuring SPAD. In addition, chlorophyll *a* fluorescence (Fv/Fm) was recorded at stage 3, 6 and 9 with the aid of a hand−held pulse modulated chlorophyll fluorometer, OS 30 (Opti–Science, Hudson, NH, US).

2. 5 Nitrogen Use Efficiency and Components of N Use Computations

The following equations were used to determine NUE and components of N use.

Nitrogen Use Efficiency (kg kg^{-1}) = Grain weight / N supplied.

Nitrogen Utilization Efficiency (kg kg^{-1}) = Grain weight / N total in plant.

Nitrogen Uptake Efficiency (kg kg^{-1}) = N total in plant / N supplied.

Percent N Recovery = [N uptake (fertilized plot) – N uptake (un–fertilized plot)] / [N applied] ×100.

Nitrogen Harvest Index (%) = (Grain N content / N total in plant).

Where N supplied is the fertilizer N applied + N supplied in the soil.

Nitrogen uptake efficiency and nitrogen harvest index were expressed as a percentage.

2. 6 Statistical Analyses

Data for phenology, physiological, growth, yield traits and NUE and its components were analyzed using SAS version 9.1 with PROC Mixed procedure as described by (Littell et al., 1996) at an alpha level of 0.05. Data for 2010 and 2011 experiments were analyzed separately due to contrasting climate conditions between the years during the growing season. For significant variables, mean separation was accomplished using protected LSD test procedure. Relationship between nutrients in the plant tissues were analyzed using the PROC REG procedure of SAS. Simple correlation was used to test the association among NUE related traits. Single degree of freedom orthogonal contrasts (linear and quadratic on N) were used to establish response of genotypes to N treatments for all NUE traits and to test genotype by N linear interaction.

Chapter 3 - Results

3. 1 Climate Conditions

Precipitation and temperature which are the two most important climatic factors that affect crop growth during the cropping season varied among the locations and years of the study. In Manhattan (Ashland Bottom) the mean maximum temperature was 28.8ºC for 2010 and 29.5ºC in 2011, while Ottawa recorded a high of 28.9ºC in 2010 and 29.6ºC in 2011. The Max temperature for Hays was not different from the other two locations with a value of 28.7ºC (Figure 1 – 3). Besides, as can be seen in Figures 4a, 5a and 6a, rainfall amounts were higher in 2010 than in 2011 in Manhattan and Ottawa thus making 2011 a dry year as compared to 2010. Crop during 2011 experienced moisture stress especially during the flowering stage for early maturing genotypes. Across all the environments in 2010, Hays had the least amount of precipitation with a total of 332 mm (Source: Data from KSU Weather Library). Relative humidity was above 70% in Manhattan and Ottawa in 2010 but slightly above 60% in 2010 for Hays and Manhattan and Ottawa in 2011 (Figures 4b, 5b and 6b). In most of the time of the growing season, evapotranspiration was higher than precipitation in all the locations in both years (Figures 7 and 8).

3. 2 Phenological Traits

There were significant ($P < 0.05$) effects of genotypes and N regimes on days to flowering across all the locations in 2010 and 2011. The time of flowering ranged from 56 to 74 d and the mean flowering days was 66 d across all genotypes. In 2010 flowering occurred at a time when temperature was optimum (28°C) hence, grain set was not

affected. However, in 2011 flowering coincided with high temperatures (> 37°C) and dry spell, hence poor seed set was observed especially for the early maturing genotypes.

There was significant ($P < 0.05$) effect of nitrogen regimes on days to flowering in 2010 in Manhattan (Unit 1 and 7) but not in Ottawa and Hays. However, in 2011 there were significant N effects across all the location. Average across the genotypes, N regimes caused genotypes which were fertilized with either 45 kg N ha^{-1} or 90 kg N ha^{-1} to flower 3 to 4 days earlier relative to the control (no inorganic N) plots. Inbred lines generally flowered late relative to the hybrids. The interaction between genotype and nitrogen was not significant for all the locations in both years.

Besides, there was a significant ($P < 0.05$) effect of genotypes on days to maturity across all locations in both 2010 and 2011. However, there was no effect of N or genotype by N interaction. Days to maturity varied from 104 d to 124 d with a mean of 115 d. Averaged across the nitrogen and years, genotypes 99480 (124 d), B35 (124 d) SC35 (130 d) were the late maturing genotypes compared to genotypes 2312, 26056, 95207, CRS1114/R45, Tx3042xTx2737, Tx2783 Tx430 and Tx7000.

3. 3 Physiological Traits During the Growing Season in 2010

3. 3. 1 Manhattan (Unit 1)

There was significant ($P < 0.05$) effect of genotypes on leaf chlorophyll content (SPAD) at all the three growth stages (vegetative, flowering and physiological maturity). At vegetative stage, genotype SC599 had higher SPAD value. However, there were no significant difference between genotypes SC599 and SC35. At flowering stage, genotype B35 recorded higher SPAD value, but it was also not significantly different from CSR1114/R45, SC35, SC599 and Tx430. While at physiological maturity, no evidence

for difference was apparent among all the stay green genotypes (B35, SC35 and SC599) and Tx430, a non–stay green genotype. However, when averaged across all the growth stages; the stay green genotypes (B35, SC35 and SC599) were generally superior in terms of SPAD value relatives to genotypes 23012, 26056, 95207, 99480, CSR1114/R45, Tx3042xTx2737, Tx2783, Tx430 and Tx7000 (Table 4).

There were significant ($P < 0.05$) effects of N levels at all the growth stages. At all the growth stages, maximum SPAD value was obtained at the optimum N regime, followed by the half recommended rate and the least at the no inorganic N (Table 4). Genotype by N interaction effect on SPAD readings was not significant at both vegetative stage and flowering stage. However, a significant interaction was evident at physiological maturity. At physiological maturity, no evidence for difference was apparent between 45 kg N ha^{-1} or 90 kg N ha^{-1} for genotypes Tx2783 and Tx430 (both non-stay green). In addition, no evidence for difference was apparent at 0 kg N ha^{-1} or 45 kg N ha^{-1} for genotypes Tx3042xTx2737 and B35. Genotype Tx7000 did not show any variation in SPAD value at all the N regimes. At 45 kg N ha^{-1}, genotype 23012 recorded higher SPAD value, while genotypes CSR1114/R45 and Tx3042xTx2737 had higher SPAD at 90 kg N ha^{-1} (Figure 9). There was no significant effect of genotype and nitrogen regimes on photochemical efficiency (Fv/Fm) at all the growth stages. Similarly, interaction between genotype and nitrogen effect on photochemical efficiency (Fv/Fm) at all the three growth stages (vegetative, flowering and physiological maturity) was not significant.

3. 3. 2 Manhattan (Unit 7)

There was significant ($P < 0.05$) effect of genotypes on leaf chlorophyll content (SPAD) at vegetative stage, flowering and at physiological maturity. At vegetative stage, genotypes SC35, SC599, 23012 and Tx430 had higher SPAD readings when compared to genotypes 95207, B35, Tx2783, Tx7000, CSR1114/R45 and Tx3042xTx2737. While genotype 99480 had the lowest SPAD value. At flowering stage, B35, SC35, SC599 and Tx430 were ranked higher when compared to genotype Tx7000. Besides, genotypes 23012, 95207 and Tx2783 had higher SPAD value when compared to genotypes 99480, CSR1114/R45 and Tx3042xTx2737. At physiological maturity, the trend was not different from what was observed at the flowering stage. Genotypes SC599, SC35, B35 and Tx7000 had significantly higher SPAD readings when compared to genotypes 95207, CSR1114/R45, Tx3042xTx2737 and Tx430. Whiles genotypes 99480, 23012, 26056 and Tx2783 recorded lowest SPAD value (Table 5).

There were significant ($P < 0.05$) effects of N regimes on SPAD readings at all the growth stages. SPAD readings ranged from 43.7 – 55.9 across all the growth stages (Table 5). At vegetative and flowering stage leaf chlorophyll content were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly higher at 0 kg N ha^{-1}. At physiological maturity, SPAD reading was significantly lower at 90 kg N ha^{-1} (45.9) when compared to 0 kg N ha^{-1} (49.5) or 45 kg N ha^{-1} (47.4).

Genotype by N interaction effect on SPAD was significant at all the growth stage. At vegetative stage, genotypes 26056, SC35 and Tx7000 had similar SPAD values at all the N regimes when compared to the other genotypes. However, at 0 kg N ha^{-1} or 45 kg N ha^{-1} genotypes 23012, Tx2783 and Tx430 had similar SPAD values but were

significantly higher at 90 kg N ha^{-1}. While at 0 kg N ha^{-1} or 90 kg N ha^{-1} genotypes 99480, B35 and SC599 recorded similar SPAD value when compared to 45 kg N ha^{-1} (Figure 10 a). At flowering stage, genotypes 95207, B35, SC35, Tx430 and Tx7000 had similar SPAD values when compared to genotypes 23102, 26056, 99480, CSR1114/R45, Tx3042xTx2737, SC599 and Tx2783. While genotypes 23012, 26056 and Tx3042xTx2737 had similar SPAD readings at 0 kg N ha^{-1} and 45 kg N ha^{-1}, but was significantly higher at 90 kg N ha^{-1} (Figure 10b). At physiological maturity, there was similar response for SPAD reading among genotypes Tx430 and Tx7000 at all the N regimes when compared to the other genotypes. At 0 kg N ha^{-1} or 45 kg N ha^{-1}, genotypes 23012, 26056, CSR1114/R45 and SC599 had similar SPAD reading but was significantly higher at 90 kg N ha^{-1}. In addition, among the genotypes, 95207, Tx3042xTx2737, B35 and SC35 responded the same for SPAD value at 45 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly lower at 0 kg N ha^{-1} (Figure 10c).

There was significant ($P < 0.05$) effect of genotype on photochemical efficiency (Fv/Fm) at vegetative stage and physiological maturity. At vegetative stage, genotypes B35, 23012, 26056, 95207, CSR1114/R45, SC35, Tx4300 and Tx7000 had higher Fv/Fm value when compared to genotypes 99480, Tx3042xTx2737, Tx2783 and SC599. However, at physiological maturity, genotypes Tx3042xTx2737, B35 and Tx7000 recorded greater Fv/Fm value when compared to other genotypes (Table 5).

There was no significant effect of N regimes and interaction between genotypes and nitrogen regimes on Fv/Fm at all the growth stages (Table 5). The photochemical efficiency (Fv/Fm) value obtained at various growth stages showed the plants had gone

through some form of stress during the growing season. This is because; the values obtained at the three growth stages were below 0.83 an indication of stress.

3. 3. 3 Ottawa

There were significant ($P < 0.05$) effects of genotype on SPAD readings at the three growth stages (vegetative, flowering and physiological maturity). At vegetative stage, genotypes SC35 and Tx430 had significantly higher SPAD readings when compared to genotypes 95207, SC599 and Tx7000. Besides, genotypes 26056, CSR1114/R45 and Tx3042xTx2737 significantly had higher SPAD reading when compared to genotypes 23012, 99480 and Tx2783. Similar response was observed at flowering and physiological maturity (Table 6).

There was significant ($P < 0.05$) effect of N regimes on SPAD readings at all the growth stages. Leaf chlorophyll content was significantly higher at 90 kg N ha^{-1} (41.5) when compared to 45 kg N ha^{-1} (39.8) or 0 kg N ha^{-1} (37.5). Similar response was observed at flowering stage. However, at physiological maturity, SPAD readings were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} when compared to 0 kg N ha^{-1} (Table 6).

Genotype by N interaction effect was evident on SPAD readings at vegetative stage and flowering stage. At vegetative stage, no significant difference was apparent at all the N regimes among genotypes 95207, B35, Tx430 and Tx7000. In addition, no difference for chlorophyll content was significant at 45 kg N ha^{-1} or 90 kg N ha^{-1} among 23012, 95207, SC35 and SC599 (Figure 11a). At flowering stage, the highest SPAD value was obtained at 90 kg N ha^{-1} for genotypes 95207, Tx3042xTx2737 and SC35 (Figure 11b). Overall, when averaged across the genotypes, the lowest SPAD value was

obtained at 0 kg N ha^{-1}. However, 23012, 99480, SC35 showed no statistical difference at 0 kg N ha^{-1} and 45 kg N ha^{-1} (Figure 11b).

There were significant ($P < 0.05$) effects of genotype on photochemical efficiency (Fv/Fm) at physiological maturity. Genotypic effect showed no difference among genotypes B35, Tx2783 and Tx430 for Fv/Fm when compared to the other genotypes (Table 6).

There was no significant nitrogen regimes effect on Fv/Fm at flowering and physiological maturity. At vegetative stage, Fv/Fm was similar at 0 kg N ha^{-1} (0.71) and 90 kg N ha^{-1} (0.71) when compared to 45 kg N ha^{-1} (0.69). Besides, interaction between genotype and N regime was not significant (Table 6).

3. 3. 4 Hays

There were significant ($P < 0.05$) effects of genotype and nitrogen regime on SPAD readings at all the growth stages. Genotypic difference showed genotypes B35, SC35, SC599 and Tx2783 had significantly higher SPAD value at vegetative stage when compared to genotypes 26056 and CSR1114/R45 and Tx3042xTx2737. While genotypes 99480, 95207, 23012, Tx430 and Tx7000 had significantly lower SPAD value (Table 7). At flowering stage, genotypes B35 and SC35 were significantly ranked higher for SPAD reading when compared to genotypes 95207, CSR1114/R45, Tx3042xTx2737 and SC599. While genotypes Tx2783, Tx430, Tx7000, 99480, 26056 and 23012 had the lowest SPAD reading. At physiological maturity, genotypes B35, SC35 and SC599 had significantly higher SPAD reading when compared to genotypes CSR1114/R45 Tx3042xTx2737 and Tx430. Besides, genotypes 26056 and 23012 had significantly higher SPAD value when compared to genotypes Tx2783, 99480, 95207 and Tx7000.

When average across the genotypes, similar SPAD values were obtained at 0 kg N ha^{-1} (48.3) and 45 kg N ha^{-1} (49.8) when compared 90 kg N ha^{-1} (52.3). At flowering stage, SPAD reading was significantly lower at 0 kg N ha^{-1} (54.9) when compared to 45 kg N ha^{-1} (56.0) or 90 kg N ha^{-1} (58.9). While at physiological maturity, SPAD values were similar at 45 kg N ha^{-1} (48.1) and 90 kg N ha^{-1} (49.1) when compared to 0 kg N ha^{-1} (44.5).

Interaction between genotype and N regime effect on SPAD was significant (P = 0.001). Genotypes 23012, SC599, Tx2783 and Tx7000 had similar SPAD values at 45 kg N ha^{-1} and 90 kg N ha^{-1} when compared to the other genotypes (Figure 12). While, genotypes CSR1114/R45 and Tx430 seem not to differ in terms of SPAD value either at 0 kg N ha^{-1} or 45 kg N ha^{-1} when compared to the other genotypes.

Genotypic effect on photochemical efficiency (Fv/Fm) was significant (P = 0.05) at flowering stage, but not at vegetative and physiological maturity (Table 7). Genotypes B35, 99480, CSR1114/R45, SC35, SC599 and Tx7000 had significantly higher Fv/Fm when compared to genotypes 23012, 26056, 95207, Tx2783, Tx3042xTx2737 and Tx430. Interaction between genotype and nitrogen regimes on Fv/Fm was not significant at all the growth stages.

3. 4 Physiological Traits During the Growing Season in 2011

3.4.1 Manhattan (Unit 1)

There was significant (P < 0.05) effect of genotype and nitrogen on leaf chlorophyll content (SPAD) at all three growth stages (vegetative, flowering and physiological maturity) (Table 8). At vegetative stage, all the hybrids, B35, SC35 Tx2783 and Tx430 had significantly higher SPAD reading when compared to genotypes SC599

and Tx7000. At flowering stage, genotypes B35, CSR1114/R45, 26056, SC35, Tx3042xTx2737 and Tx430 had significantly higher SPAD value when compared to genotype 95207. While genotypes Tx2783, 99480, 23012 and Tx7000 had higher SPAD value when compared to genotype SC599. At physiological maturity, genotypes B35, CSR1114/R45, 26056, Tx2783, Tx430, SC35 and Tx3042xTx2737 and 95207 were ranked higher for SPAD reading when compared to genotypes Tx7000, 23012, 99480, SC599.

When averaged across the genotypes at vegetative stage, SPAD values were similar at 45 kg N ha^{-1} (49.0) and 90 kg N ha^{-1} (49.9) when compared to 0 kg N ha^{-1} (48.0). However, at flowering state, SPAD reading was similar at 0 kg N ha^{-1} (52.6) and 45 kg ha^{-1} (54.0) but was significantly higher at 90 kg N ha^{-1}. Similar response was observed for SPAD reading at physiological maturity.

There was significant (P = 0.05) effect of genotype on photochemical efficiency (Fv/Fm) at vegetative stage (Table 8). Genotypes 95207, 26056, 23012, 99480, B35, and Tx430 had significantly higher Fv/Fm when compared to genotypes CSR1114/R45/ Tx7000, Tx3042xTx2737, SC35, SC599 and Tx2783. Interaction between genotypes and nitrogen regimes was not significantly at all the growth stages.

3. 5. 1 Manhattan (Unit 7)

There was significant (P = 0.001) effect of genotypes on leaf chlorophyll content (SPAD) at vegetative, flowering and physiological maturity (Table 9). At vegetative stage, genotypes B35 and SC35 had significantly higher SPAD reading when compared to all the hybrids, Tx2783 and Tx430. While genotypes SC599 and Tx7000 had lowest SPAD value. At flowering stage, genotypes B35 and SC35 again recorded higher SPAD

value when compared to genotypes Tx430, 26065, 99480 and Tx3042xTx2737. While genotypes SC599, Tx2783, Tx7000, CSR1114/R45, 95207 and 23012 had lowest SPAD value. At physiological maturity, genotypes B35, SC35 and 26056 and CSR1114/R45 had significantly higher SPAD value when compared to genotypes 95207, 99480, Tx3042xTx2737 and Tx430. While genotypes Tx2783, 23012 and Tx7000 had lowest SPAD reading.

There was no significant effect of nitrogen regime on SPAD reading at flowering and physiological maturity. At vegetative stage, SPAD reading was lower (48.4) at 0 kg N ha^{-1} when compared at 45 kg N ha^{-1} (49.6) or 90 kg N ha^{-1} (50.2). Genotype by N interaction effect on SPAD reading was significant (P = 0.05) at vegetative stage. At all the N regimes, SPAD reading was similar among genotypes 26056, 99480, CSR1114/R45, SC35 and SC599. At 0 kg N ha^{-1} or 45 kg N ha^{-1}, no significant difference was observed between genotypes 23012 and Tx3042xTx2737 when compared to the other genotypes. While genotypes B35 and Tx430 had similar SPAD value at 0 kg N ha^{-1} and 90 kg N ha^{-1} when compared to 45 kg N ha^{-1} (Figure 13a).

There was no significant effect of genotypes on photochemical efficiency (Fv/Fm) at all the three growth stages. However, significant (P = 0.05) effect of nitrogen regimes was observed at flowering and physiological maturity. At flowering stage, Fv/Fm was similar at 0 kg N ha^{-1} and 45 kg N ha^{-1} but significantly lower at 90 kg N ha^{-1}. While at physiological maturity, lower Fv/Fm value was observed at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1} (Table 9).

3. 5. 2 Ottawa

There was significant ($P < 0.05$) effect of genotype on leaf chlorophyll content (SPAD) at vegetative stage, flowering and physiological maturity (Table 10). At vegetative stage, genotypes CSR1114/R45, SC35, Tx430, B35, Tx3042xTx2737, 95207, 26056 and 23012 had higher SPAD value when compared to genotypes 99480 and Tx7000. While genotypes SC599 had lowest SPAD value. At flowering stage, genotypes Tx430, CSR1114/R45, SC35 and 26056 were ranked higher when compared to genotypes Tx3042xTx2737 and B35. While genotypes 95207, 99480, Tx2783, 23012, SC599 and Tx7000 had lowest SPAD value. At physiological maturity, genotypes 26056, CSR1114/R45, Tx3042xTx2737, B35, SC35, Tx2783 and Tx430 had higher SPAD reading when compared to 23012, 95207, 99480 and Tx7000.

There was significant ($P < 0.05$) effect of nitrogen regimes on SPAD at flowering and physiological maturity (Table 10). At both growth stages, no statistical difference was apparent at 45 kg N ha^{-1} or 90 kg N ha^{-1} relative to the 0 kg N ha^{-1}.

Genotype by N interaction effect on SPAD was significant ($P < 0.05$) at physiological maturity. No variation in SPAD values was observed between genotypes CSR1114/R45 and Tx2783 at 0 kg N ha^{-1} or 45 kg N ha^{-1}. In addition, at 45 kg N ha^{-1} or 90 kg N ha^{-1}, genotypes Tx430 and 95207 recorded similar SPAD value when compared to the other genotypes. While at optimum N regime, genotypes 26506, 99480, Tx3042xTx2783 and Tx2783 recorded higher SPAD values when compared to other genotypes (Figure 13b).

No significant ($P < 0.05$) effect of genotypes, N regimes and genotypes by N regime interaction effects were observed for Fv/Fm at all the three growth stages (vegetative, flowering and physiological maturity) (Table 10).

3. 5 Growth Traits During the Growing Season in 2010

3. 5. 1 Manhattan (Unit 1)

Growth traits (plant height, green leaves, total leaves, percentage senesced leaves and total biomass at vegetative, flowering and physiological maturity) are presented in Table 11. There were significant ($P < 0.05$) effects of genotype on all growth traits with the exception of plant height. The number of green leaves varied from 7 – 9 across the genotypes, while total number of leaves at physiological maturity varied from 14 – 16. Genotype CSR1114/R45 (54.3%) recorded the highest percentage senesced leaves when compared to other genotypes. However, no evidence for difference was apparent among 23012, 26056, 92507, 99480 SC35 and Tx2783. When averaged across the nitrogen regimes, percentage leave senesced varied from 39.7 – 54.3%.

Among the genotypes, 99840 (3,352 kg ha^{-1}) had the highest biomass at vegetative stage, but was not statistically different from CSR1114/R45. Total biomass varied from 1,606 – 3,352 kg ha^{-1}. However, at flowering Tx2783 (9,713 kg ha^{-1}) had the highest biomass. When averaged across the nitrogen regimes, total biomass ranged from 4,538 – 9,713 kg ha^{-1}. At physiological maturity, hybrid 99840 (13,236 kg ha^{-1}) had higher biomass when compared to the other genotypes.

There were significant ($P < 0.05$) effects of nitrogen regimes on total number of leaves at maturity, percentage senesced leaves and total biomass at all the three growth stages. Total number of leaves increased as the N rate was increased. Percentage

senesced leaves were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but significantly greater than 0 kg N ha^{-1}. Furthermore, across the growth stage, maximum biomass was obtained at 90 kg N ha^{-1}, followed by 45 kg N ha^{-1} and the least at 0 kg N ha^{-1}. Interaction between genotype and nitrogen was not significant for all growth traits.

3. 5. 2 Manhattan (Unit 7)

There were significant ($P < 0.05$) effects of genotype on all growth traits (Table 12). For plant height, the shortest genotype was 95207 (91.8 cm), while the tallest genotypes were 26056, 99480, Tx3042xTx2737, Tx2783 and Tx430. Overall, plant height ranged from 91.8 – 119 cm. Number of green leaves varied from 6.0 – 9.0, while total number of leaves at physiological maturity varied from 12 –14. Percentage leaves senesced was higher among genotypes Tx430 and Tx7000, while genotype SC599 recorded the lowest percentage senesced leaves when compared to the other genotypes.

Total biomass at the growth stages showed varied response among the genotypes. At vegetative stage, hybrids 99480 (3,421 kg ha^{-1}) and CSR1114/R45 (3,569 kg ha^{-1}) produced higher biomass relative to rest of the genotypes. At this stage, amount of biomass ranged from 1,684 – 3,569 kg ha^{-1}. At flowering stage, hybrid 99480 (11,469 kg ha^{-1}) again had the highest total biomass. The mean biomass at flowering stage varied from 6,885 – 11,469 kg ha^{-1}. At physiological maturity, the trend was not different from what was observed at vegetative stage. Total biomass varied from 9,496 – 17,962 kg ha^{-1} when averaged across the N regimes. Hybrids 99480 and CSR1114/R45 had greater biomass when compared to the other genotypes.

Significant ($P < 0.05$) nitrogen effect was evident for all the growth traits (except total number of leaves) (Table 12). No significant difference was apparent between 0 kg

N ha^{-1} and 45 kg N ha^{-1} relative to 90 kg N ha^{-1} for plant height. Number of green leaves and percentage senesced leaves were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but significantly greater at 0 kg N ha^{-1}. Total biomass was higher at 90 kg N ha^{-1}, followed by 45 kg N ha^{-1} and the least at 0 kg N ha^{-1}.

Genotype by N interaction had no statistically significant effect on all the growth traits with the exception of percentage senesced leaves. The highest percent leaf senesced was observed at 0 kg N ha^{-1} regimes (Figure 14a). However, genotype Tx3042xTx2737 had similar percentage leaves senesced at all the N regimes. While at 45 kg N ha^{-1} or 90 kg N ha^{-1} genotypes SC35 and SC599 had the same percentage leaves senesced when compared to the other genotypes. All hybrids as a group had the lowest percentage senesced leaves at the optimum N level (except genotype Tx3042xTx2737). Interestingly, within the inbred lines; Tx430 recorded the highest percentage leaf senesced at the 90 kg N ha^{-1} (Figure 14a).

3. 5. 3 Ottawa

There was significant ($P < 0.05$) effect of genotype and nitrogen on all the growth traits (Table 13). Average across N regimes, plant height varied from 95.9 – 125 cm. Similarly green leaves and total number of leaves at physiological maturity varied from 7 – 9 and 14 – 16 respectively. The percentage leaves senesced range from 40.0 – 46.7%.

For total biomass at vegetative stage, all the hybrids (except genotype Tx3042xTx2737) were statistically not different from each other relative to the inbred line as a group. However, at flowering and physiological maturity, genotypes 26056, 99480 and CSR1114/R45, all post−flowering drought tolerant, produced higher amount of biomass compared to the other genotypes.

Effect of nitrogen on the growth traits showed plant height was similar at 0 kg N ha^{-1} and 45 kg N ha^{-1} relative to 90 kg N ha^{-1}. Higher number of green leaves, total number of leaves and the least senesced leaves were obtained at the optimum N regime compared to 0 kg N ha^{-1} or 45 kg N ha^{-1}. Besides, at all the growth stages, maximum biomass was obtained at 90 kg N ha^{-1}, followed by 45 kg N ha^{-1} and the least at 0 kg N ha^{-1}.

There was no interaction between genotype and nitrogen for all the growth traits with the exception of percentage senesced leaves. No variation in percentage leaf senesced was evident at all the N regimes for genotype SC35 (Figure 14b). In addition, similar response was observed at 0 kg N ha^{-1} and 45 kg N ha^{-1} among genotypes 99480, CSR1114/R45 and Tx7000. Besides, genotype Tx2783 showed no difference at 45 kg N ha^{-1} or 90 kg N ha^{-1}. Overall, the highest percentage leaf senesced was obtained at 0 kg N ha^{-1} regimes and the lowest at 90 kg N ha^{-1} (Figure 14b).

3. 5. 4 Hays

Significant ($P < 0.05$) effect of genotypes on all the growth traits was observed (Table 14). Genotypes Tx3042xTx2737, B35 and Tx2783 were significantly taller than 23012, 26056, and 99480, CSR1114/R45, SC35, SC599 Tx430 and Tx7000. While genotype 95027 was the shortest. Total green leaves and total number of leaves ranged from 8 – 11 and 13 – 16 respectively. Genotypes 99480 and Tx7000 had significantly greater percentage leaves senesced when compared to genotypes 23012, 26056, 95207, and Tx2783. While Tx430, SC35, B35 and CSR1114/R45 had lowest senesced leaves.

The results also showed that, among the genotypes and across the growth stages hybrid 26056 consistently produced the highest amount of biomass. Total biomass varied

from 1,826 – 3,791 kg ha^{-1}, 3,822 – 9,711 kg ha^{-1} and 5,624 – 15,257 kg ha^{-1} at vegetative, flowering and physiological maturity respectively.

There was no significant effect of nitrogen on plant height, total number of leaves, percentage senesced leaves and total biomass at vegetative stage. Total number of leaves was significantly lower (9) at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1} (10). The total biomass at flowering was significantly higher at 90 kg N ha^{-1} (7,510 kg ha^{-1}) compared to 45 kg N ha^{-1} (6,752 kg ha^{-1}) or 0 kg N ha^{-1} (5,685 kg ha^{-1}). Similar responses were observed for biomass at maturity. Interaction between genotype and nitrogen was not significant for all growth traits.

3. 6 Growth Traits During the Growing Season in 2011

3. 6. 1 Manhattan (Unit 1)

There was significant ($P < 0.05$) effect of genotype on all growth traits (Table 15). Plant height varied from 93.8 – 121 cm among the genotypes. Similarly, green leaves and total number of leaves varied from 6 – 9 and 12 – 15 respectively. Genotypes 95207, CSR1114/R45, Tx3042xTx2737 SC599 Tx2783 and Tx7000 had significantly greater percentage leaves senesced compared to genotypes 99480, B35, and Tx430. While genotype SC35 had lowest percentage leaves senesced.

At vegetative stage, hybrids as a group and genotype Tx7000 had higher total biomass when compared to genotypes B35, SC35, SC599, Tx2783 and Tx430. At flowering stage, genotypes 99480, Tx2783, SC599, CSR1114/R45 and 26056 had higher biomass compared to the other genotypes. Besides, at physiological maturity, genotypes 99480, 23012, CSR1114/R45 and Tx3042xTx2737 had higher total biomass when

compared to genotypes 26056, 95207 and B35. While genotypes SC35, SC599, Tx2783, Tx430 and Tx7000 had lowest total biomass.

There was no significant effect of nitrogen on all the growth traits with the exception of total biomass at flowering and physiological maturity. The biomass production at flowering was significantly higher at 90 kg N ha^{-1} (7,355 kg ha^{-1}) when compared to 45 kg N ha^{-1} (6,680 kg ha^{-1}) or 0 Kg N ha^{-1} (5,613 kg ha^{-1}). However, at physiological maturity, the response to N was similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} when compared to 0 kg N ha^{-1}. Interaction between genotype and nitrogen was not significant for all growth traits.

3. 6. 2 Manhattan (Unit 7)

There was significant ($P < 0.05$) effect of genotype on all growth traits in 2011 (Table 16). Among the genotypes, Tx7000 (91.6 cm) and 23012 (125 cm) were the shortest and tallest respectively. The total green leaves varied from 5.2 – 9.3, while total number of leaves at physiological maturity ranged from 12 – 14. Genotypes B35 and SC35 had significantly greater number of senesced leaves when compared to genotypes 26056, 99480, CSR1114/R45 Tx3042xTx2737, SC599 and Tx2783. While genotypes 23012, 95207, Tx430 and Tx7000 had lowest number of senesced leaves.

Genotypes 23012, 26056, 95207 and CSR1114/R45 had significantly higher total biomass at vegetative stage when compared to other genotypes. At flowering stage, genotypes 99840, SC599 Tx2783 26056, 95207, CSR1114/R45 Tx3042xTx2737 and Tx7000 produced higher total biomass when compared genotypes 23012, B35 and Tx430. At physiological maturity, all the hybrids (except genotype Tx3042xTx2737) and

Tx2783 significantly had higher total biomass when compared genotypes SC599, Tx430 and Tx7000. While genotypes B35 and SC35 had lowest total biomass.

There was no significant nitrogen effect on plant height, total number of leaves and total biomass at vegetative stage (Table 16). Total green leaves were significantly lower at 0 kg N ha^{-1} (6.5) when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1} (7.1). Total biomass at flowering was significantly higher at 90 kg N ha^{-1} (6931 kg) when compared to 45 kg N ha^{-1} (5,951 kg ha^{-1}) or 0 kg N ha^{-1} (5,344 kg ha^{-1}). Similar response was observed for biomass at physiological maturity. Interaction between genotype and nitrogen was not significant for all growth traits.

3. 6. 3 Ottawa

There was a significant ($P < 0.05$) effect of genotypes on all the growth traits (Table 17). Plant height varied from 80.9 – 110 cm when averaged across the N regimes. Genotypes Tx7000, 26056, 99480, CSR1114/R45, Tx3042xTx2737, SC599, Tx2783 and Tx430 were significantly taller when compared to 23012 and SC35. While genotypes 95207 and B35 were the shortest. The number of green leaves and total number of leaves ranged from 6 – 9 and 11 – 14 respectively when averaged across the N regimes. All the hybrids as group (except genotype 26056) and Tx7000 significantly had greater number of senesced leaves when compared to genotypes B35, SC35, SC599, Tx2783 and Tx430.

At vegetative stage, the mean total biomass varied from 883.3 – 1197 kg ha^{-1}. Genotypes 95207, 23012, 26056, SC599 and Tx7000 produced higher amount of biomass when compared to other genotypes. At flowering stage genotypes B35 and SC35 and SC599 had higher amount of biomass when compared to genotypes 23012, 26056, 95207, 99480 CSR1114/R45, Tx2783 and Tx7000. While genotypes Tx3042xTx2737

and Tx430 had lowest total biomass. At maturity, genotypes SC599, 99840, CSR1114/R45, B35, SC35 and Tx7000 produced greater amount of biomass when compared to other genotypes.

There was no significant effect of nitrogen levels on plant height, total number of leaves and total biomass at vegetative stage. The number of green leaves was significantly higher at 90 kg N ha^{-1} (7.9) when compared to 0 kg N ha^{-1} (6.6) or 45 kg N ha^{-1} (7.0). The percentage leaves senesced was significantly lower (40.0%) at 90 kg N ha^{-1} when compared to 0 kg N ha^{-1} (48.7%) or 45 kg N ha^{-1} (45.8%). The amount of total biomass produced at flowering stage and physiological maturity were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} when compared to 0 kg N ha^{-1}. Interaction between genotype and nitrogen was not significant for all growth traits.

3. 7 Yield and Yield Components in 2010

3. 7. 1 Manhattan (Unit 1)

There was a highly significant ($P < 0.0001$) effect of genotype on all yield and yield components (grain yield (kg ha^{-1}), harvest index (HI), 200 kernel weight and number of kernel (m^{-2}) (Table 18). Among the genotypes, hybrids 26056, 99480 23012 and CSR1114/R45 had higher grain yield when compared to genotypes 95207 and Tx3042xTx2737. While genotypes B35, SC35 and Tx430 had the lowest grain yield. For HI when averaged across nitrogen regimes, varied from 0.25 – 0.47. Genotypes 95207, 23012 and Tx2783 had greater HI when compared to the other genotypes. The mean 200 kernel weight ranged from 4.03 – 5.36 g when averaged across the N levels. Genotypes Tx430 and CSR1114/R45 had significantly higher 200 kernel weight when compared to genotypes 99480 and Tx7000. In addition, genotypes 23012, 26056, 95207 and SC599

had significantly heavier 200 kernel weight when compared to genotypes Tx3042xTx2737 and B35. While genotypes SC35 and Tx2783 had lowest 200 kernel weight.

There was no significant nitrogen effect on HI and 200 kernel weight (Table 18). Maximum grain yield was obtained at 90 kg N ha^{-1} (3,836 Kg ha^{-1}) when compared to 0 kg N ha^{-1} (3,373 kg ha^{-1}) or 45 kg N ha^{-1} (3,575 kg ha^{-1}). Similar response was observed for kernel number (m^{-2}). Interaction between genotype and nitrogen was not significant for yield and yield components.

3. 7. 2 Manhattan (Unit 7)

There was significant ($P < 0.05$) effect of genotype on grain yield, HI, 200 kernel weight and number of kernel (m^{-2}) (Table 19). Genotypes 23012, 26056, 99480 and CSR1114/R45 had significantly higher grain yield when compared to genotypes Tx3042xTx2737, Tx2783, Tx7000 and 95207. While genotypes B35, SC35, SC599 and Tx730 had lowest grain yield. Harvest index was significantly similar among genotypes Tx7000, 23012, 26056, 99480, Tx3042xTx2737 and Tx2783 when compared to other genotypes. Genotypes Tx430 recorded heavier 200 kernel weight, when compared to genotypes CSR1114/R45 and SC35. In addition, genotypes 26056, 95207, Tx3042xTx2737 and B35 significantly had heavier kernel weight when compared to genotypes SC599, 23012, 99480 and Tx2783. For kernel number (m^{-2}), no significant difference was observed among genotypes 99408, 23012, 26056 and Tx2783, when compared to other genotypes.

There was no significant effect of nitrogen regimes on HI and kernel number (m^{-2}). Grain yield and 200 kernel weight was similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but

was significantly lower at 0 kg N ha^{-1}. Besides, the interaction effect between genotypes and nitrogen regimes on grain yield and 200 kernel weight was significant (Figure 15a and b). Grain yield was similar at all the nitrogen regimes for genotypes SC35, Tx2783 and Tx430. At 0 kg N ha^{-1} and 45 kg N ha^{-1}, no significant difference was observed between genotypes 95207 and Tx7000. While at 45 kg N ha^{-1} or 90 kg N ha^{-1}, there was similar response among genotypes 23012, 99480 and Tx3042xTx2737 (Figure 15a). Kernel weight did not seem to vary among genotypes 23012, 26506, 99480, CSR1114/R45, B35, SC599 and Tx2783 at the three N regimes. While at 45 kg N ha^{-1} and 90 kg N ha^{-1}, no significant difference was observed between Tx3042xTx2737 and Tx430 (Figure 15b).

3. 7. 3 Ottawa

Effects of genotypes on grain yield and yield components were highly significant ($P < .0001$) (Table 20). There was similar response to N for grain yield among all the hybrids, when compared to the inbred lines. The mean grain yield varied from 622 – 2,767 kg ha^{-1}. Similarly, HI varied from 0.29 – 0.36 when averaged across the nitrogen levels. Genotypes 23012, 26056, 95207, 99480 and Tx2783 had significantly greater HI when compared to CSR1114/R45, Tx3042xTx2737, SC35, SC599 and Tx7000. For 200 kernel weight, genotypes Tx430, 26056, 95207, Tx3042xTx2737, SC35 and Tx7000 were ranked higher when compared to other genotypes. Variation among the genotypes showed genotypes 99480 and Tx3042xTx2737 had significantly higher number of kernels (m^{-2}) when compared genotypes 23012, 26056, 95207 and CSR1114/R45. In addition, genotypes SC599, Tx430 and Tx7000 had significantly greater kernel number (m^{-2}) when compared to genotypes SC35 and Tx2783.

Effect of N regimes on grain yield, HI and kernel number (m^{-2}) was significant ($P < 0.05$). Grain yield was significantly lower (1,535 kg ha^{-1}) at 0 kg N ha^{-1} when compare to 45 kg N ha^{-1} (1,851 kg ha^{-1}) or 90 kg N ha^{-1} (2,265 kg ha^{-1}). Similar response was observed for HI and kernel number (m^{-2}). Interaction between genotype and nitrogen was not significant for yield and yield components.

3. 7. 4 Hays

Yield and yield components is presented in Table 21. There was significant ($P < 0.05$) effect of genotype on all yield traits. Among the genotypes, 26056 and 99480 had higher grain yield when compared to genotypes 23012, 95207, CSR1114/R45, Tx3042xTx2737, B35, Tx2783 and Tx7000. While genotypes SC35, SC599 and Tx430 had lowest grain yield. Harvest index varied from 0.24 – 0.49 when averaged across the N regimes. Genotype 95207 had significantly higher HI when compared to genotypes 23012, 99480, Tx3042xTx2737, SC35, SC599, Tx2783 and Tx7000. While genotypes 26056, CSR1114/R45, B35 and Tx430 had lowest HI. Besides, genotypes Tx3042xTx2737, Tx430, Tx7000, 26056 and 95207 had heavier kernel weight, when compared to other genotypes. The effect of genotypes on kernel number showed that genotypes 99480 and Tx3042xTx2737 were superior to other genotypes. However, when averaged across the nitrogen regimes, genotypes B35, SC35 and Tx430 significantly had lowest kernel number.

There was significant ($P < 0.05$) effect of nitrogen regimes on grain yield, HI and kernel number (Table 21). Maximum grain yield was obtained at 90 kg N ha^{-1} when compared to 0 kg N ha^{-1} or 45 Kg N ha^{-1}. For HI and kernel numbers (m^{-2}), similar responses were observed. Interaction effect of genotype and N on grain yield, HI and

kernel number was significant ($P < 0.05$). For grain yield, there was no significant effect of nitrogen regimes between genotypes CSR1114/R45 and Tx430 when compared to other genotypes. At 0 kg N ha^{-1} or 45 kg N ha^{-1}, genotypes 23012, Tx3042xTx2373 and Tx2783 were significantly not different for grain yield when compared to other genotypes. While genotypes SC35 and SC599 showed similar response at 45 kg N ha^{-1} and 90 kg N ha^{-1} (Figure 16a).

Besides, there was no significant difference for kernel numbers (m^{-2}) at all the N levels between genotypes 23012 and 99480 when compared to other genotypes. At 0 kg N ha^{-1} or 45 kg N ha^{-1}, genotypes Tx3042xTx2737, B35 and SC35 were not significantly different from each other. However, genotype Tx7000 had similar kernel numbers at 0 kg N ha^{-1} and 90 kg N ha^{-1}. When averaged across the genotypes, more kernel numbers were obtained at 90 kg N ha^{-1}, followed by 45 kg N ha^{-1} and the least at 0 kg N ha^{-1} between Tx3042xTx2737 and Tx430 (Figure 16b).

Harvest index for the genotypes at all the N regimes is presented in Figure 16c. At all the nitrogen regimes, no significant difference was observed between genotypes 26056 and Tx7000 relative to other genotypes. At 0 kg N ha^{-1} or 45 kg N ha^{-1}, no difference was apparent among genotypes 99480, B35 and Tx2783 when compared to other genotypes. A similar response was observed at 45 kg N ha^{-1} and 90 kg N ha^{-1} among genotypes SC35, SC599 and Tx430 when compared to other genotypes.

3. 8 Yield and Yield Components in 2011

3. 8. 1 Manhattan (Unit 1)

Yield and yield component (grain yield (kg ha^{-1}), HI 200 kernel weight and number of kernels (m^{-2}) is presented in Table 22. There was significant ($P < 0.05$) effect

of genotype on grain yield and yield components in 2011. Genotype 99480 had significantly higher grain yield when compared to genotypes 26056 and 95207. In addition, genotypes Tx3042xTx2737 and 23012 had higher grain yield when compared to genotype Tx2783. While genotypes B35, Tx430, SC35, TX7000, CSR1114/R45 and SC599 had lowest grain yield. Among the genotypes, 95207, Tx2783, 23012, 99480, Tx3042xTx2737 had significantly greater HI when compared to other genotypes. For 200 kernel weight it was observed that genotypes CSR1114/R45, Tx430, Tx7000, Tx2783, 26056 and 95207 were ranked higher when compared to genotypes B35, 99840, SC35, SC599 and 23012. While genotype Tx3042xTx2737 had lowest 200 kernel weight.

Besides, when averaged across the nitrogen regimes, kernel number (m^{-2}) varied from 3,764 – 17,812. It was observed that, number of kernels (m^{-2}) was associated with genotypes with higher grain yield. As was expected, genotype 99480 a high yielding hybrid had significantly higher number of kernels (m^{-2}) when compared to other genotypes.

There was significant ($P < 0.05$) effect of nitrogen regimes on all yield traits with the exception of HI. Grain yield was significantly higher at 90 kg N ha^{-1} (2,616 kg ha^{-1}) when compared to 0 kg N ha^{-1} (2,288 kg ha^{-1}) or 45 kg N ha^{-1} (2,421 kg ha^{-1}). Heavier kernel weight was obtained at 45 kg N ha^{-1} (5.9 g), but was not significantly different from 90 kg N ha^{-1} (5.7 g) when compared to 0 kg N ha^{-1}. Significantly lower kernel numbers were obtained at 0 kg N ha^{-1} (8,249) when compared to 45 kg N ha^{-1} (8,414) or 90 kg N ha^{-1} (9,226).

There was significant ($P < 0.05$) genotype and N levels interaction effect on grain yield and 200 kernel weight (Figures 17a and b). Genotypes B35 and SC35 had similar

grain yield at 45 kg N ha^{-1} and 90 kg N ha^{-1} (Figure 17a). While genotype SC599 had similar grain yield at 0 kg N ha^{-1} and 45 kg N ha^{-1}, but was significantly lower at 90 kg N ha^{-1}. Genotype CSR1114/R45 had similar grain yield at 0 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly lower at 45 kg N ha^{-1}. Among the genotypes, 23012 and SC35 had similar 200 kernels weight at all the nitrogen regimes when compared to the other genotypes (Figure 17b).

3. 8. 2 Manhattan (Unit 7)

There was significant ($P < 0.05$) effect of genotype on yield and components of yield in 2011 (Table 23). Genotypes 99480 and 26056 had higher grain yield when compared to genotypes 23012, Tx3042xTx2737, Tx2783 and 95207. While genotypes CSR1114/R45, B35, SC35, SC599, Tx430 and Tx7000 had lowest grain yield. For HI, genotypes 99480, 95207 and Tx95207 were ranked higher when compared to genotypes 23012 and Tx2783. While genotypes B35, SC35, SC599, 26056, Tx430, CSR1114/R45 and Tx7000 had significantly lower HI. Genotypic variation showed that 200 kernels weight varied from 4.8 – 6.24 g when averaged across the nitrogen regimes. Genotypes Tx7000 and CSR1114/R45 had significantly heavier kernel weight when compared to genotypes 26056 and Tx430. In addition, genotype Tx3042xTx2737 had significantly heavier kernel weight, when compared to genotype SC35. While genotypes Tx2783, SC599, B35, 99840, 95207 and 23012 had lowest kernel weight. When averaged across the nitrogen regimes kernel numbers (m^{-2}) varied from 3,833 – 17,911. Among the genotypes, 99480 and 95207 were superior to genotypes 23012, 26056, Tx3042xTx2737 and Tx2783 for kernel numbers. Whiles genotypes B35, CSR1114/R45, SC35, SC599, Tx430 and Tx7000 had significantly lowest kernel number (m^{-2}).

There was no significant nitrogen regimes effect on HI (Table 23). Maximum grain yield was obtained at 45 kg N ha^{-1} (2,787 kg ha^{-1}) and 90 kg N ha^{-1} (2,803 kg ha^{-1}) when compared to 0 kg N ha^{-1} (2,490 kg ha^{-1}). Similar response was observed for 200 kernel weight. Kernel numbers (m^{-2}) were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but significantly higher than 0 kg N ha^{-1}.

Interaction between genotype and nitrogen effect on grain yield was significant (P = 001). The interaction showed there was no yield difference for genotype 99840 at all the nitrogen regimes when compared to other genotypes. There were similar grain yield at 0 kg N ha^{-1} and 45 kg N ha^{-1} but significantly higher at 90 kg N ha^{-1} for genotype Tx430. At 0 kg N ha^{-1}, genotypes 26056, 95207, SC599 and Tx2783 had higher grain yield when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1}. While genotypes 26056, 95207, CSR1114/R45, Tx3042xTx2737, B35 and Tx7000 had lowest grain yield at 90 kg N ha^{-1} when compared to 0 kg N ha^{-1} or 45 kg N ha^{-1} (Figure 18).

3. 8. 3 Ottawa

There was significant ($P < 0.05$) effect of genotype on grain yield and yield components in 2011 (Table 24). When averaged across the nitrogen levels, grain yield varied from 1,318 – 4,467 kg ha^{-1}. Genotype 99480 was superior to genotypes 26056, CSR1114/R45, Tx3042xTx2737, Tx2783 and Tx7000 for grain yield. In addition, genotype 23012 had higher grain yield when compared to genotypes B35, SC599, and Tx430. While genotype 95207 had lowest grain yield. For HI, genotypes 23012, 95207, CSR1114/R45, 26056, 99480, TxTx2783 and Tx7000 were ranked higher when compared to genotypes B35, SC35, SC599, Tx430 and Tx3042xTx2737. Variability among the genotypes showed that, genotypes 99480, Tx2783, Tx0000 had kernel weight

less than 5.0 g, while the rest of the genotypes had kernel weight greater than 5.0 g. Kernel numbers (m^{-2}) was significantly greater for genotypes 99480, when compared to genotypes CSR1114/R45, Tx7000, 26056 and Tx2783. While genotypes 23012 and SC599 had significantly higher kernel numbers when compared to genotypes B35, 95207, SC35, Tx430 and Tx3042xTx2737.

There were no significant effect of N regimes on HI and 200 kernel weight. Grain yield were similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly greater than 0 kg N ha^{-1}. Similar response was observes for kernel number (m^{-2}). Interaction between genotype and nitrogen was not significant for yield and yield components.

3. 9 Leaves, Stems and Total N Uptake at Flowering Stage in 2010

3. 9. 1 Manhattan (Unit 7)

There was significant ($P < 0.05$) effect of genotype on leaves, stems and total N at flowering stage (Table 25). Genotypes 99840, 26056 and CSR1114/R45 had significantly higher amount of N in the leaves at flowering stage when compared to genotype Tx7000. Whiles genotypes 23012, 95207, Tx3042xTx2737, B35, SC35, SC599, Tx2783 and Tx430 had lowest leave N. For stem N at flowering stage, genotypes Tx7000, Tx2783, SC599, Tx3042xTx2737, CSR1114/R45, 95207 and 26056 were ranked higher when compared to genotypes SC35, B35, Tx430, 99480 and 23012. Total N (leave and stem) varied from 97.1 – 138 kg ha^{-1}. All the hybrids and genotypes SC599, Tx2783 and Tx7000 had significantly greater total N when compared to genotypes B35, SC599 and Tx430.

Effect of N regimes on leaves, stems and total N was significant ($P < 0.05$). Nitrogen uptake in the leaves were lower (64.3 kg ha^{-1}) at 0 kg N ha^{-1} when compared to

45 kg N ha^{-1} (66.9 kg ha^{-1}) or 90 kg N ha^{-1} (72.6 kg ha^{-1}). Stem and total N were similar at 0 kg N ha^{-1} and 45 kg N ha^{-1} but significantly higher at 90 kg N ha^{-1}. Interaction between genotype and nitrogen was not significant for leaves, stems and total N.

3. 10 Leaves, Stems, Grain and Total N Uptake at Maturity in 2010

3. 10. 1 Manhattan (Unit 7)

Effect of genotype on N in plant parts was significant ($P < 0.05$) at physiological maturity (Table 26). Nitrogen in the leaves showed that genotypes CSR1114/R45, 26506, 95207, SC599 and Tx2783 were ranked higher when compared to other genotypes. For stem N, genotypes 26056, 95207, CSR1114/R45 and Tx2783 were superior to genotypes 99480, SC35 and Tx430. While genotypes B35, Tx3042xTx2783, 23012, SC599 and Tx7000 had significantly lowest stem N. When averaged across N regimes, grain N varied from 103 – 199 kg ha^{-1}. Genotype CSR1114/R45 had significantly greater grain N when compared to genotypes 23012, 26056, 95207, 99480, Tx3042xTx2737 and Tx7000. In addition, genotypes Tx430, B35 and 23012 were superior to genotypes SC35 and SC599. Total N (leaves, stems and grain) was significantly higher for genotype CSR1114/R45 when compared to genotypes 95207, 99480, Tx7000 and 26056. It was evident that, genotypes Tx2783, 23012 and Tx3042xTx2737 translocated greater amount of N to the plant parts when compared to genotypes SC35, Tx430, SC599 and B35.

Effect of N regimes on N in the plant parts at maturity was significant ($P < 0.05$). Leaves and stems N were similar at 0 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly higher at 45 kg N ha^{-1}. However, for grain N, similar response was observed at 45 kg N ha^{-1} and 90 kg N ha^{-1} but significantly lower at 0 kg N ha^{-1}. Total N was significantly

higher (163 kg ha^{-1}) at 45 kg N ha^{-1} when compared to 90 kg N ha^{-1} (149 kg ha^{-1}) or 0 kg N ha^{-1} (116 kg ha^{-1}).

Interaction between genotypes and nitrogen effect on leaves stems and total N was significant (Figure 19a, b and c). It was evident that leaves N was similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} for genotype Tx3042xTx2737. However, at 45 kg N ha^{-1} or 90 kg N ha^{-1}, genotypes CSR1114/R45 and Tx2783 were significantly not different from each other (Figure 19a). For stem N, all the hybrids (except genotype CSR1114/R45), genotypes SC35 and Tx2783 were superior at 45 kg N ha^{-1} when compared 0 kg N ha^{-1} or 90 kg N ha^{-1} (Figure 19b). Total N was similar at all the N regimes for genotype 95207 when compared to other genotypes. While genotypes 23012, CSR1114/R45 and Tx430 had similar total N at 45 kg N ha^{-1} or 90 kg N ha^{-1} but significantly lower at 0 kg N ha^{-1} (Figure 19c).

3. 11 Leaves, Stems and Total N Uptake at Flowering Stage in 2010

3. 11. 1 Ottawa

There was a significant ($P < 0.05$) effect of genotype on leaves, stems and total N (leaves and stems) (Table 27). When averaged across the N regimes, leaves N uptake varied from 14.0 – 21.4 kg ha^{-1} at flowering. Among the genotypes, hybrids 99480, 26056, CSR1114/R45 and 23012 mobilized more from the soil to leaves when compared to other genotypes. For stems N, it was evident that, genotypes CSR1114/R45, Tx7000, 99480, 26056, Tx2783 and SC35 were ranked higher when compared to genotypes SC599, Tx3042xTx2737, 23012, Tx430 and 95207. Total nitrogen uptake when average across the nitrogen regimes varied from 28.4 – 42.7 kg ha^{-1}. Genotypes CSR1114/R45, 99480, 26056, Tx7000, Tx2783 and 23012 mobilized more N from the soil to the leaves

and stems at flowering when compared to genotypes SC35, Tx3042xTx2737, SC599, Tx430 and 95207. There was no significant effect of nitrogen on leaves, stems and total nitrogen uptake. Similarly, interaction between genotype and nitrogen was not significant (Table 27).

3. 12 Leaves, Stems, Grain and Total N Uptake at Maturity in 2010

3. 12. 1 Ottawa

Effect of genotype on leaves, stems, grain and total N (leaves, stems and grain) uptake at physiological maturity was significant ($P < 0.05$). Nitrogen uptake in the leaves showed genotype SC35 was superior, but was not significantly different from genotypes 26506, 95207, 99480, CSR1114/R45 and Tx430 (Table 28). Among the genotypes Tx7000, SC599 and 23012 had significantly lower leaves N at maturity. For stem N when averaged across the N regimes varied from 6.1 – 11.4 kg ha^{-1}. Genotypes SC35, CSR1114/R45, Tx3042xTx2737, 99480 and Tx2783 had significantly greater stem N when compared to genotypes 23012, 26056 and 95207. While genotypes SC599, Tx430 and Tx7000 had lowest stem N. It was evident that all the hybrids (except genotype Tx3042xTx2737), Tx2783 and Tx7000 had significantly higher grain N when compared to genotypes Tx3042xTx2737 and SC35. While genotypes SC599 and Tx430 had lowest grain N. Total N uptake varied from 30.6 – 54.2 kg ha^{-1}. Overall, genotypes 99480, Tx2783, 26056, CSR1114/R45, SC35, 99480 and 23012 translocated more N to the plant parts when compared to Tx7000. While genotypes SC599 Tx430 and Tx3042xTx2737 had significantly lower total N uptake.

There was no significant effect of N regimes on leaves and stems N. Grain N was significantly lower (21.9 kg ha^{-1}) at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} (26.3 kg

ha^{-1}) or 90 kg N ha^{-1} (33.0 kg ha^{-1}). Total N uptake was similar at 0 kg N ha^{-1} and 45 kg N ha^{-1} but was significantly higher at 90 kg N ha^{-1}. Interaction between genotype and nitrogen was not significant for leaves, stems, grain and total N uptake (Table 28).

3. 13 Leaves, Stems and Total N Uptake at Flowering Stage in 2011

3. 13. 1 Manhattan (Unit 7)

There was significant ($P < 0.05$) effect of genotype on leaves, stems and total N (leaves and stems) uptake at flowering stage (Table 29). Leaves N when averaged across the nitrogen regimes varied from 45.4 – 60.5 kg ha^{-1}. Among the genotypes, 99480, 26056, CSR1114/R45, 95207, SC599, Tx2783 and Tx7000 mobilized more N from the soil and translocated it to the leaves when compared to genotypes B35, SC35, Tx430, Tx3042xTx2737 and 23012. However, genotypes Tx2783, SC35, Tx7000, Tx3042xTx2737 and 99480 had significantly greater stem N when compared to genotypes SC599, 95207, 26056, CSR1114/R45, Tx430, B35 and 23012. Total N uptake varied from 77.3 – 101 kg ha^{-1}. Besides, among the genotypes, 99480, Tx2783, Tx7000, SC599, 95207 and 26056 mobilized more N from the soil to the leaves and stems when compared to other genotypes.

There was no significant effect of nitrogen on total N uptake at flowering stage. The nitrogen uptake in the leaves was significantly lower (40.3 kg ha^{-1}) at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} (53.4 kg ha^{-1}) or at 90 kg N ha^{-1} (64.4 kg ha^{-1}). Similar response was observed for stem N (Table 29). Interaction between genotype and nitrogen was not significant for leaves, stems and total N uptake (Table 29).

3. 14 Leaves, Stems, Grain and Total N Uptake at Maturity in 2011

3. 14. 1 Manhattan (Unit 7)

There was a significant ($P < 0.05$) effect of genotype on N uptake in all plant parts including total N uptake (Table 30) at physiological maturity. It was evident that, genotypes CSR1114/R45, B35 and Tx430 had significantly higher leaves N when compared to genotypes SC35, Tx7000 and 26056. While genotypes 95207, 99480, SC599, Tx2783 and Tx3042xTx2737 had lowest stems N. Stem N varied from 7.7 – 15.8 kg ha^{-1} when averaged across the N regimes. Similarly, grain N ranged from 36.7 – 58.0 kg ha^{-1}. Genotypes 99480, 23012, Tx2783, CSR1114/R45 and 26056 translocated more N to the grain when compared to genotypes Tx7000, Tx3042xTx2737 and 95207. While genotypes SC35, SC599, B35 and Tx430 translocated less N to the grain. It was observed that genotypes CSR1114/R45, B35, 99480, Tx2783 and Tx7000 mobilized more N from the soil to the plant parts when compared to genotypes 23012, 26056 and 95207. While genotypes SC599, SC35, Tx3042xTx2737 and Tx430 significantly had lowest total N uptake.

There was significant ($P < 0.05$) effect of nitrogen regimes on all plant parts including total N uptake (Table 30). The leaves N were similar at 0 kg N ha^{-1} (21.4 kg ha^{-1}) and 45 kg N ha^{-1} (22.8 kg ha^{-1}) but significantly greater at 90 kg N ha^{-1} (24.1 kg ha^{-1}). However, stem N was significantly lower (9.6 kg ha^{-1}) at 0 kg N ha^{-1}, when compared to 45 kg N ha^{-1} (12.5 kg ha^{-1}) or at 90 kg N ha^{-1} (12.7 kg ha^{-1}). Similar response was observed for grain N concentration and total N. Interaction between genotype and nitrogen was not significant for leaves, stems, grain and total N uptake (Table 30).

3. 15 Leaves, Stems and Total N at Flowering Stage in 2011

3. 15. 1 Ottawa

There was a significant ($P < 0.05$) effect genotype on leaves, stems and total nitrogen (leaves, stems) uptake at flowering stage (Table 31). Leaves N when averaged across the N regimes varied from 17.8 – 44.9 kg ha^{-1}. Genotypes SC35 and B35 had significantly higher leave N when compared to genotypes SC599 and Tx2783. While genotypes Tx3042xTx2737, 23012, Tx7000, 95207, CSR1114/R45, 99480 and Tx430 had lowest leaves N at flowering. Similar response was observed for stem N and total N uptake. There was no significant effect of nitrogen regimes on leaves, stem and total N uptake at flowering. Similarly, interaction between genotype and nitrogen regimes was not significant (Table 31).

3. 16 Leaves, Stems, Grain and Total N Uptake at Maturity in 2011

3. 16. 1 Ottawa

Effect of genotypes on N uptake in plant parts and total N uptake was significant ($P < 0.05$) at physiological maturity. Leave N was significantly higher for genotype B35 when compared to genotypes SC35 and 26056. While genotypes 99480, SC599, Tx7000, CSR1114/R45, 95207, Tx430 and Tx2783 had significantly higher leaves N when compared to genotypes Tx3042xTx2737 and 23012. Besides, genotype B35 significantly mobilized more N from the soil to the stems when compared to other genotypes (Table 32). Grain N when averaged across the N regimes varied from 31.6 – 52.0 kg ha^{-1}. Besides, genotypes Tx3042xTx2737, 23012, 99480, 95207, Tx7000, Tx430 and 26056 translocated more N to the grain when compared to genotypes Tx2783, SC599 and

CSR1114/R45. While genotypes B35 and SC35 had significantly lowest grain N. There was similar response among all the genotypes (except genotypes SC35 and CSR1114/R45) for total N uptake (Table 32).

There was significant ($P < 0.05$) effect of N regimes on N uptake in all plant parts and total N. Leave N was similar at 0 kg N ha^{-1} (9.5 kg ha^{-1}) and 45 kg N ha^{-1} (10.6 kg ha^{-1}) but significantly greater at 90 kg N ha^{-1} (12.2 kg ha^{-1}). Stem N was significantly lower (4.1 kg ha^{-1}) at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} (6.0 kg ha^{-1}) or 90 kg N ha^{-1} (6.0 kg ha^{-1}). Similar responses were observed for grain N and total N uptake (Table 32). Interaction between genotype and nitrogen regimes was not significant for leaves, stem, grain and total N uptake (Table 32).

3. 17 Nitrogen Use Efficiency and Components of N Use in 2010

3. 17. 1 Manhattan (Unit 7)

3. 17. 1. 1 Nitrogen Use Efficiency (NUE)

There was significant ($P < 0.05$) effect of genotype and nitrogen regimes on nitrogen use efficiency (NUE) and components of N use. Interaction between genotypes and nitrogen regimes was not significant for NUE and component of N use (Table 33). Among the genotypes, 99480, 23012, Tx3042xTx2737 and B35 had significantly higher NUE when compared to genotypes Tx700, CSR1114/R45, 26056 and 95207. While genotypes SC35, SC599 and Tx2783 had lowest NUE. For N regimes on NUE, similar response was observed at 45 kg N ha^{-1} and 90 kg N ha^{-1} but significantly higher at 0 kg N ha^{-1}.

3. 17. 1. 2 Nitrogen Utilization Efficiency

Nitrogen utilization was significantly higher for genotypes 99480, B35, 23012 and Tx3042xTx2737 when compared to genotypes Tx7000, Tx430 and CSR1114/R45. While genotypes Tx2783, SC35, SC599, 26056 and 95207 had lowest nitrogen utilization efficiency. It was evident that nitrogen utilization was significantly higher at 0 kg N ha^{-1} (50.2 kg kg^{-1}) when compared to 45 kg N ha^{-1} (62.8 kg kg^{-1}) or 90 kg N ha^{-1} (40.8 kg kg^{-1}).

3. 17. 1. 3 Nitrogen Uptake Efficiency

Nitrogen uptake efficiency when averaged across the nitrogen regimes varied from 58.2 – 82.5%. In addition, genotypes 99480, B35, 23012 and CSR1114/R45 had significantly higher nitrogen uptake efficiency when compared to genotypes 26056, Tx2783, CSR1114/R45, Tx430 and Tx700. While genotype SC35 had lowest nitrogen uptake efficiency. Besides, similar nitrogen utilization efficiency response was observed at 45 kg N ha^{-1} and 90 kg N ha^{-1}, but was significantly higher at 0 kg N ha^{-1}.

3. 17. 1. 4 Fertilizer N Recovery

Results obtained using the difference method showed fertilizer N recovery varied from 2.1 – 52.0%. Besides, genotype 26056 had significantly higher fertilizer N recovery when compared to genotype 23012. However, genotypes CSR1114/R45 had significantly higher fertilizer N recovery when compared to genotypes Tx430 and SC35. While genotypes B35, 95207, 99480, Tx2783, Tx3042xTx2737, Tx7000 and SC599 had lowest fertilizer N recovery. A Significantly higher fertilizer N recovery was observed at 45 kg N ha^{-1} (26.8%) when compared to 90 kg N ha^{-1} (13.7%).

3. 17. 1. 5 Nitrogen Harvest Index (NHI)

Genotypic variation showed genotypes 99480, Tx3042xTx2737 and B35 had significantly higher NHI, but were not significantly different from 23012, 26506, CSR1114/R45, Tx430 and Tx7000. While genotypes SC35, Tx2783, SC599 and 95207 had lowest NHI. It was observed that, NHI was similar at 0 kg N ha^{-1} and 90 kg N ha^{-1} but significantly lower at 45 kg N ha^{-1}.

3. 17. 2 Ottawa

3. 17. 2. 1 Nitrogen Use Efficiency (NUE)

There was significant ($P < 0.05$) effect of genotype on NUE and Components of N use (Table 34). When averaged across the N regimes, NUE varied from 18.0 – 35.4 kg kg^{-1}, Genotypes 26056, 95207, 99480, 23012 and CSR1114/R45 had significantly higher NUE when compared to genotypes Tx2783, Tx7000, Tx3042xTx2737 and SC35. While genotypes SC599 and Tx430 had lowest NUE.

Effect of N regimes on NUE was significant ($P < 0.001$). Nitrogen use efficiency was significantly higher at 0 Kg N ha^{-1} when compared 45 kg N ha^{-1} or 90 kg N ha^{-1}. Interaction between genotypes and N regimes was significant. At all the N levels genotypes 99480, 26506, 95207, CSR1114/R45 and 23012 showed similar response (Figure 20a). A quadratic response of N was highly significant ($P = 0.0001$).

3. 17. 2. 2 Nitrogen Utilization Efficiency

Genotypic variation showed that hybrids 26056, 95207, 99480, 23012 and CSR1114/R45 were ranked higher for nitrogen utilization efficiency when compared to

genotypes Tx7000, Tx3042xTx2737 and Tx2783. While genotypes SC35, SC599 and Tx430 had significantly lowest nitrogen utilization efficiency.

There was significant (P = 0.001) effect of nitrogen regimes on utilization efficiency. At 45 kg N ha^{-1} or 90 kg N ha^{-1}, similar response was observed but significantly lower at 0 kg N ha^{-1}. Besides, interaction effect between genotype and nitrogen regimes was significant (P = 0.001). Nitrogen utilization efficiency was similar at 0 kg N ha^{-1} and 45 kg N ha^{-1} for genotypes 23012, 26056 and Tx3042xTx2737 when compared to 0 kg N ha^{-1} (Figure 20b). However, for genotype Tx2783 similar response was observed at 0 kg N ha^{-1} and 90 kg N ha^{-1} when compared to 45 kg N ha^{-1}. In addition, genotypes 26056, 95207, 99480, Tx3042xTx2737, Tx430 and Tx7000 had significantly higher nitrogen utilization efficiency at 90 kg N ha^{-1} when compared to 0 kg N ha^{-1} or 45 kg N ha^{-1}. While genotype SC599 had higher N utilization efficiency at 45 kg N ha^{-1} when compared to 0 kg N ha^{-1} or 90 kg N ha^{-1} (Figure 20b). A linear response of N was highly significant (P = 0.0001).

3. 17. 2. 3 Nitrogen Uptake Efficiency

Effect of genotypes on N uptake efficiency showed that, genotypes 26056, 99480, 23012, 95207, CSR1114/R45, SC35, Tx2783 and Tx7000 were ranked higher when compared to genotypes Tx3042xTx2737, SC599 and Tx430.

There was significant (P = 0.001) effect of nitrogen regimes on N uptake efficiency. Increasing N regimes decreased uptake efficiency among all the genotypes. Interaction effect between genotype and nitrogen was also significant (P = 0.001). At 90 kg N ha^{-1}, genotypes 23012, 26056, 965207, 99480, CSR1114/R45 and Tx2737 had significantly higher N uptake efficiency when compared to genotypes Tx3042xTx2737,

SC35, SC599, Tx430 and Tx7000 (Figure 21a). Similar response was observed among the genotypes at 45 kg N ha^{-1} when compared to 90 kg N ha^{-1}. Quadratic response of N was significant (P = 0.001).

3. 17. 2. 4 Fertilizer N Recovery

Fertilizer N recovery based on the difference method varied from 12.1– 37.5%. Genotypes Tx7000, Tx2737, 23012, 26056, CSR1114/R45, SC35 and SC599 had significantly higher fertilizer N recovery when compared to genotypes 95207 and Tx430. While genotypes Tx3042xTx2737 and 99480 had lowest fertilizer N recovery. There was no significant effect of nitrogen regimes effect on fertilizer N recovery. Similarly, interaction between genotypes and nitrogen regimes was not significant (Table 34)

3. 17. 2. 5 Nitrogen Harvest Index (NHI)

It was observed that genotypes Tx2783, 26056, 95207, 99480, Tx7000, 23012 and CSR1114/R45 were ranked higher for nitrogen NHI when compared to genotypes SC599, SC35, Tx430 and Tx3042xTx2737. Effect of N regime on NHI was significant (P = 0.001). There were similar NHI at 45 kg N ha^{-1} and 90 kg N ha^{-1} but significantly lower at 0 kg N ha^{-1}.

Besides, interaction effect between genotype and N regimes was significant (P <0.05). Similar response for NHI was observed among genotypes 26056, 95207, 99480 and Tx2783 at 0 kg N ha^{-1} and 45 kg N ha^{-1} but significantly higher at 90 kg N ha^{-1}. Besides, genotypes CSR1114/R45 and Tx3042xTx2737 had higher NHI at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1} (Figure 21b). The results also showed a linear response of N was significant (P = 0.001).

3. 18 Nitrogen Use Efficiency and Components of N Use in 2011

3. 18. 1 Manhattan (Unit 7)

3. 18. 1. 1 Nitrogen Use Efficiency (NUE)

There was significant ($P < 0.05$) effect of genotypes on NUE and components of nitrogen use (Table 35). For NUE when averaged across the nitrogen regimes varied from 17.2 – 28.4 kg kg^{-1}. Genotypes 23012 and 99480 had significantly higher NUE when compared to genotypes 95207, 26056, CSR1114/R45, Tx3042xTx2737 and Tx2783. It was evident that, genotypes SC599, B35 and Tx7000 had significantly higher NUE when compared to genotypes SC35 and Tx430.

Effect of nitrogen regimes was highly significant ($P = 0.0001$). NUE was significantly higher at 0 kg N ha^{-1} (31.1 kg kg^{-1}) when compared to 45 kg N ha^{-1} (19.8 kg kg^{-1}) or 90 kg N ha^{-1} (15.0 kg kg^{-1}). The interaction effect between genotypes and nitrogen regimes was significant ($P = 0.011$). At 0 kg N ha^{-1}, genotypes 23012, 26056, 95207, 99480, Tx3042xTx2737, SC35 and Tx2783 had significantly higher NUE when compared to genotypes CSR1114/R45, B35, SC35, Tx430 and Tx7000 (Figure 22a). Similar response was observed at 45 kg N ha^{-1} and 90 kg N ha^{-1} among the genotypes. A significant ($P = 0.001$) quadratic response on N was evident.

3. 18. 1. 2 Nitrogen Utilization Efficiency

Among the genotypes, Tx700 and Tx430 recorded higher N utilization efficiency when compared to genotypes CSR1114/R45, Tx2783, SC599 and SC35. Similarly, genotypes B35, Tx3042xTx2737, 99480 and 95207 had higher nitrogen utilization efficiency when compared to genotypes 23012 and 26056. There was no significant

effect of nitrogen regimes on nitrogen utilization efficiency. Similarly, interaction between genotype and N regimes was not significant.

3. 18. 1. 3 Nitrogen Uptake Efficiency

No genotypic variation was observed for the entire hybrids as a group, B35, Tx430 and Tx7000 for N uptake efficiency when compared to genotypes SC35, SC599 and Tx2783. There was significant (P = 0.001) effect of nitrogen regimes on nitrogen uptake efficiency. Nitrogen effect was significantly higher at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1}. Interaction between genotype and nitrogen regime was not significant.

3. 18. 1. 4 Fertilizer N Recovery

Fertilizer N recovery varied from 2.7 – 27.5% when averaged across the nitrogen regimes (Table 35). Genotypes Tx2783, Tx430, 23012 and 26056 recorded higher fertilizer N recovery when compared to genotypes 95207, 99480 and CSR1114/R45. While genotypes B35, SC35, SC599, Tx7000 and Tx3042xTx2737 had significantly lower fertilizer N recovery. There was no significant effect of nitrogen regimes on fertilizer N recovery. Similar effect was observed for the interaction between genotype and N regime.

3. 18. 1. 5 Nitrogen Harvest Index (NHI)

Nitrogen harvest index, an indication of the genotype ability to remobilize N from the leaves and stem to grain varied from 47.6 – 70.2 kg kg^{-1}. Among the genotypes, hybrids 23012, 26506, CSR1114/R45, Tx3042xTx2737 and inbred line Tx2783

remobilized higher amount N to the grain when compared to genotype 95207. While genotypes 99480, SC35, B35, Tx430 and Tx7000 had lowest NHI.

There was significant ($P < 0.05$) effect of nitrogen regimes on NHI. It was evident that NHI was similar at 0 kg N ha^{-1} and 45 kg N ha^{-1} but significantly higher at 90 kg N ha^{-1} (Table 35). Interaction between genotype and nitrogen regime was not significant.

3. 18. 2 Ottawa

3. 18. 2. 1 Nitrogen Use Efficiency (NUE)

There were significant ($P < 0.05$) effects of genotype as well as N regimes on NUE and components of N use (Table 36) in Ottawa. When averaged across the N regimes NUE varied from 19.7 – 42.9 kg kg^{-1}. Genotypes 99480, 26056, Tx7000, 23012, and CSR1114/R45 recorded significantly higher NUE when compared to genotypes 95207, Tx2783, Tx430, Tx3042xTx2737 and SC599. While genotypes B35 and SC35 had lowest NUE.

The effect on N regime showed a significantly higher NUE was obtained at 0 kg N when compared to 45 kg N or 90 kg N ha^{-1}. Interaction between genotype and nitrogen regime was significant ($P = 0.001$). At 0 kg N ha^{-1}, genotypes 23012 and CSR1114/R45 had similar NUE. However, genotypes 26056, 99480 and Tx700 had higher NUE at 0 kg N ha^{-1} when compared to genotypes 95207, Tx3042xTx2783, SC599, Tx2783 and Tx7000. While genotypes B35, SC35 and Tx430 had lowest NUE at 0 kg N ha^{-1}. In addition, genotypes 23012, 26056, 99480, Tx430 and Tx7000 recorded higher NUE at 45 kg N ha^{-1} when compared to other genotypes. While genotypes 23012, 26056, 99480, CSR1114/R45, SC599, Tx2783 and Tx7000 had higher NUE at 90 kg N ha^{-1} when compared to genotypes 95207, Tx3042Tx2737, B35, SC35 and Tx430 (Figure 22b).

3. 18. 2. 2 Nitrogen Utilization Efficiency

Effect of genotypes on N utilization efficiency showed that genotypes 99480, Tx7000, CSR1114/R45, Tx2783 and 23012 ranked higher when compared to genotypes Tx3042xTx2737, SC599, 95207, Tx430 and 26056. While genotypes B35 and SC35 had the lowest N utilization efficiency.

Nitrogen utilization efficiency was similar at 45 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly higher at 0 kg N ha^{-1}. Interaction between genotype and nitrogen regime was not significant

3. 18. 2. 3 Nitrogen Uptake Efficiency

No significant difference was apparent for uptake efficiency among the genotypes (except genotypes 25606 and Tx430). Averaged across the N regimes, uptake efficiency varied from 60.1 – 64.4%. Effect of N levels showed significantly higher N uptake efficiency was obtained at 0 kg N ha^{-1} when compared to 45 kg N ha^{-1} or 90 kg N ha^{-1}. Interaction between genotype and nitrogen regime was not significant (Table 36).

3. 18. 2. 4 Fertilizer N Recovery:

Among the genotypes, Tx430 26056 and 23012 were most efficient in N recovery, but was not significantly different from genotypes 23012 and 26506 when compared to genotypes Tx7000, 99480, CSR1114/R45, Tx3042xTx2737 and 95207. Whiles genotypes Tx2783, SC35, SC599 and B35 had lowest fertilizer N recovery (Table 36).

Effect of N regime showed significantly higher fertilizer N recovery was obtained at 45 kg N ha^{-1} relative to 90 kg N ha^{-1}. There was a significant ($P = 0.001$) effect of genotype and nitrogen regime interaction on fertilizer N recovery. Among the genotypes

23012, 26056, Tx3042xTx2737, Tx430 had higher N recovery at 45 kg N ha^{-1} when compared to 90 kg N ha^{-1} (Figure 23). However, at 45 kg N ha^{-1} or 90 kg N ha^{-1}, N recovery was similar for genotype SC35 when compared to the other genotypes.

3. 18. 2. 5 Nitrogen Harvest Index (NHI)

When averaged across the N regimes, NHI varied from 50.6 – 81.3 kg kg^{-1}. Genotypes Tx3042xTx2737, Tx7000, SC599, 23012, 95207, 99480 and 26056 had significantly higher NHI when compared to genotypes Tx2783and Tx430. While genotypes SC35 and B35 had lowest NHI (Table 36).

Nitrogen effect showed similar response for NHI at 45 kg N ha^{-1} and 90 kg N ha^{-1} but was significantly lower at 0 kg N ha^{-1}. Interaction between genotype and nitrogen regime was not significant.

3. 19 Percentage Change

There were significant differences in response of genotypes to N levels for total biomass and grain yield. These responses were quantified as percentage change in total biomass or grain yield as N change from 0 kg N ha^{-1} to 45 kg N ha^{-1}, 45 kg N ha^{-1} to 90 kg N ha^{-1} and 0 kg N ha^{-1} to 90 kg N ha^{-1} are showed in Figures 24 through 35. Overall based on N response, genotypes were divided into three categories. Genotypes with percentage change < 25%, 25 – 50% and > 50%. In Manhattan (Unit 1) based on the criterion indicated above all the genotypes (except genotype Tx7000) had percentage change < 25% as N changed from 0 kg N ha^{-1} to 45 kg N ha^{-1} (Figure 24a). The percentage change (decrease or increase) from 45 kg N ha^{-1} to 90 kg N ha^{-1} for the different genotypes were all < 25% (except genotype 99480) (Figure 24b). When N

regimes increased from 0 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 23012, 26056, 99480, CSR1114/R45, Tx3042xTx2737, B35, SC35,and Tx430 had percentage change < 25%, while genotypes 95207 and SC599 from 25 – 50% and genotype Tx7000 had > 50% (Figure 24c).

At physiological maturity, as N increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, genotypes 23012, 26056, 95207, 99480, CSR1114/R45, Tx3042xTx2737, SC35, SC599, Tx2783 and Tx430 had percentage change < 25% (Figure 25a). While genotypes B35 and Tx7000 from 25 – 50%. However, when nitrogen regime increased from 45 kg N ha^{-1} to 90 kg N ha^{-1} it was observed that all the genotypes had percentage change < 25% (Figure 25b). Similar response was observed as N changed from 0 kg N ha^{-1} to 90 kg N ha^{-1} (Figure 25c).

The response of the genotypes to N regime for grain yield showed that, as N increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, genotypes 26056, 95207, 99480, CSR1114/R45, Tx3042xTx2737, SC35, SC599, Tx2783 had percentage change < 25% (Figure 26a). While genotype 23012 from 25 – 50% and TX7000 had > 50%. Besides, as N levels increased from 45 kg N ha^{-1} to 90 kg N ha^{-1}, all the genotypes had percentage change < 25% (Figure 26b). However, as N regime increased from 0 kg N to 90 kg N ha^{-1}, all the genotypes (except genotype Tx7000) had percentage < 25% (Figure 26c).

The response of the genotypes to N in Manhattan (Unit 7) is presented in Figures 3.27 – 3.29. The genotypic variation among the genotypes for total biomass at flowering stage showed that, as N regime increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, all the genotypes had percentage change < 25% (Figure 27a). The results also showed that genotypes all the genotypes(except genotype SC35) had percentage change < 25% as N

levels increased from 45 kg N ha^{-1} to 90 kg N ha^{-1} (Figure 27b). Besides, as N levels increased from 0 kg N ha^{-1} to 90 kg N ha^{-1}, all the genotypes (except genotype B35) had percentage change < 25% (Figure 27c).

At physiological maturity, as N changed from 0 kg N ha^{-1} to 45 kg N ha^{-1} percentage change for total biomass was < 25% for genotypes 95207, 99480, CSR1114/R45, Tx3042xTx2737, B35, SC35, SC599,Tx430 and Tx7000. While genotypes 23012 and Tx2783 from 25 – 50% and genotype 26056 had >50% (Figure 28a). However, as N levels increased from 45 kg N ha^{-1} to 90 kg N ha^{-1}, the response among all the genotypes were < 25% (Figure 28b). Besides, as N changed from 0 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 26056, 95207, 99480, CSR1114/R45, Tx3042xTx2737, B35, SC35, Tx430 and Tx7000 had percentage change < 25%, while genotypes 23012, SC599 and Tx2783 from 25 – 50% (Figure 28c).

Percentage change (decrease or increase) for grain yield is presented in Figure 3.29. Percentage change as N increased from 0 kg N ha^{-1} to 45 kg N ha^{-1} was < 25% among all the genotypes (Figure 29a). However, as N changed from 45 kg N ha^{-1} to 90 kg N ha^{-1}, all the genotypes (except genotype 99480) also had percentage change < 25% (Figure 3.29b). In addition, among all the genotypes, percentage change was < 25% as N levels increased from 0 kg N ha^{-1} to 90 kg N ha^{-1} (Figure 29c).

Percentage change (decrease or increase) at Ottawa is presented in Figures 3.30 – 3.32. At flowering stage, it was observed that total biomass was < 25% as N changed from 0 kg N ha^{-1} to 45 kg N ha^{-1} among all the genotypes (except genotypes B35 and Tx7000) (Figure 3.30a). Besides, as N increased from 45 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 23012, 26056, 95207, 99480, Tx3042xTx2737, B35, SC35, SC599, Tx2783,

Tx430 and Tx7000 had percentage change < 25, while genotype CSR1114/R45 from 25 – 50 % (Figure 30b). The results also demonstrated that, genotypes 23012, 26056, 95207, 99480, Tx3042xTx2737, SC35, Tx2783 and Tx430 had percentage change < 25% as N changed from 0 kg N ha^{-1} to 90 kg N ha^{-1}, while genotypes B35 and SC599 from 25 – 50% and genotype Tx7000 had > 50% (Figure 30c).

At maturity as N regimes were increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, genotypes 23012, 26056, 95207, 99480, CSR1114/R45, Tx3042xTx2737, B35, SC35 and Tx430 had percentage change of < 25%. While genotypes Tx2783 and Tx7000 from 25 – 50% and genotype SC599 had > 50% (Figure 31a). Total biomass was < 25% as N levels was increased from 45 kg N ha^{-1} to 90 Kg N ha^{-1} (Figure 31b) among all the genotypes. However, as N regime was changed from 0 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 23012, 95207, 99480, CSR1114/R45, Tx3042xTx2737, B35, SC35, SC599 and Tx2783 had percentage < 25%. While genotypes 26056 and Tx430 from 25 – 50% and genotype Tx7000 had > 50% (Figure 31c).

Percentage change (decrease or increase) for grain yield in presented in Figure 3.32. When N regime was increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, genotypes 95207, 99480, Tx3042xTx2737 CSR1114/R45, B35, SC35, Tx2783 and Tx430 had percentage change < 25%. While genotypes 23012, 26056, SC599 and Tx7000 from 25 – 50% (Figure 32a). Besides, as N regime was changed from 45 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 23012, 26056, 95207, 99480, Tx3042xTx2737, SC35, SC599 Tx2783, Tx430 and Tx7000 had percentage change < 25%, while genotypes 99820, CSR1114/R45 and B35 had from 25 – 50%. At N levels of 0 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 95207, CSR1114/R45, Tx3042xTx2737, B35, SC35, Tx430 and Tx7000 had percentage change

< 25%. While genotypes 26056, 99480, SC599 and Tx2783 from 25 – 50% and genotype 23012 had > 50% (Figure 32c).

The response of genotypes to N levels for total biomass and grain yield at Hays is presented in Figures 33 – 35. At flowering stage, genotypic differences showed that as N regimes was increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, genotypes 23012, 26056, 99480, CSR1114/R45, Tx3042xTx2737, B35 and Tx7000 had percentage change < 25%. While genotypes 95207, SC35, Tx2783, and Tx430 had from 25 – 50% and genotype SC599 had > 50% (Figure 33a). At N regimes of 45 kg N ha^{-1} to 90 kg N ha^{-1}, all the genotypes (except genotypes Tx2783 and Tx340) had percentage change < 25% (Figure 33b). However, as N regime was increased from 0 kg N ha^{-1} to 90 kg N ha^{-1}, genotypes 26056, 95207, B35 and SC35 had percentage change < 25%, while genotypes 23012, 99480, CSR1114/R45, Tx3042xTx2737, SC599 and Tx7000 from 25 – 50% and genotypes Tx2783 and Tx430 had > 50% (Figure 33c).

Genotypic variation among the genotypes again showed that, at physiological maturity when N regime was from 0 kg N ha^{-1} to 45 kg N ha^{-1} genotypes 99480, Tx3042xTx2737, B35 and Tx7000 had percentage change < 25%. While genotypes 23012, 95207, CSR1114/R45, SC599, Tx2783 and Tx430 from 25 − 50% and genotypes 26056 and SC35 had > 50% (Figure 34a). At N regimes of 45 kg N ha^{-1} to 90 kg N ha^{-1}, all the genotypes (except genotype 95207) had percentage change < 25% (Figure 34b). It was observed that, as N regimes increased from 0 kg N ha^{-1} to 90 kg N ha^{-1} genotype 23012 had percentage change < 25%, while genotypes 99480, Tx3042xTx2737, B35, Tx2783, and Tx7000 from 25 − 50% and genotypes 26056, 95207, CSR1114/R45, SC35. SC599 and Tx430 had > 50% (Figure 34c).

Percentage change for grain yield is presented in Figure 35. As N levels increased from 0 kg N ha^{-1} to 45 kg N ha^{-1}, genotypes 26056, 95207, 99480, CSR1114/R45, Tx3042xTx2737, SC35, Tx2783, Tx430 and Tx7000 had percentage change < 25%, while genotypes 23012, B35 and SC599 from 25 − 50% (Figure 35a). Percentage change among all the genotypes was < 25% as N level increased from 45 kg N ha^{-1} to 90 kg N ha^{-1} (Figure 35b). Besides, genotypes 26056, 95207, 99480, Tx3042xTx2737, CSR1114/R45, B35, SC35, Tx2783, Tx430 and Tx7000 had percentage change < 25% as N regimes increased from 0 kg N ha^{-1} to 90 kg N ha^{-1}, while genotypes 23012 and SC599 from 25 – 50% (Figure 35c).

3. 20 Correlations

The relationship between photochemical efficiency (Fv/Fm) and leaf chlorophyll content at vegetative, flowering and physiological maturity did not fit to linear best (Figures 36a, b and c). The relationship between leaf chlorophyll content and grain yield was significant at vegetative and flowering stages. At vegetative stage there was a positive relationship (r^2 = 0.37, P = 0.04, n = 12). Similar relationship was observed at flowering stage (r^2 = 0.35, P = 0.04, n = 12) (Figures 37a and b). There was no significant relationship between Fv/Fm and grain yield at all the growth stages (Figure 38).

Besides, correlation of grain to biomass at the three growth stages (vegetative stage, flowering, and physiological maturity) is showed in Figure 39. The relationship at vegetative stage was significant and positive and linear (r^2 = 0.72, P = 0.0004, n = 12) (Figure 3.39a). At flowering stage, the relationship was also significant, positive and linear (r^2 = 0.45, P = 0.0126, n = 12) (Figure 39b). Similar response was observed at physiological maturity, but the relationship was stronger than what was observed at

flowering stage (r^2 = 0.74, P = 0.006, n = 12) (Figure 39c). Thus, the contribution of biomass to grain yield was more significant at maturity than at flowering stage.

The relationship between grain yield and harvest index, 200 kernel weight and kernel number m^{-2} is showed in Figure 40. There was significant and positive relationship between grain yield and harvest index (r^2 = 0.63, P = 0.002, n =12) (Figure 40a). Grain yield and 200 kernel weight was not significant (r^2 = 0.003, P = 0.8579, n = 12). However, the relationship between grain yield and kernel number (m^{-2}) was linear (r^2 = 0.98, P = 0.0001, n = 12) (Figure 40c). Thus, kernel number per m^{-2} contributed the highest to grain yield than 200 kernel weight.

In Manhattan (Unit 7), the relationships between grain yield and grain N; r^2 = 0.94, P = 0.0001, n = 12, total biomass and grain N, r^2 = 0.81, P = 0.0001, n = 12 and total nitrogen uptake at maturity (kg N ha^{-1}) r^2 = 0.89, P = 0.0001, n = 12 was linear and positive (Figures 41a, b and c). Similar positive relationship was observed between grain yield and grain N; total biomass and grain N; and grain N and total N uptake at Ottawa. (Figures 42a, b and c).

Chapter 4 - Discussion

At the current rate of increasing cost of nitrogen fertilizer it is important to develop strategies or efficient use of N. One of the strategies to use N more efficiently is development of N use efficient genotypes. In some parts of the world (eg. SSA) where farmers do not use N fertilizer due to high cost and unavailability, it is more critical to develop and use genotypes, which will be both efficient in uptake and utilization of the applied and available nutrient.

4. 1 Climatic Conditions

The growing season (May – October) for 2010 and 2011 were contrasting. In 2010, there was more rainfall especially in the months of June through to September (Figure 4 – 6). Thus, the growing season was wet resulting in adequate soil moisture particularly during the grain–filling period. However, in 2011 long dry spell and high temperatures were detrimental to crop growth. Throughout the growing season, evapotranspiration (ET) was more than precipitation (Figure 7 – 8). Thus, the lower the in–season precipitation, the higher the amount of stored soil water extracted and the lower the residual soil water. When there is not enough stored soil water to meet ET demand the crop will be water stressed and photosynthetic processes and carbohydrate synthesis will decrease, and grain yield will be adversely affected. This could also explain the variability in grain yield across all the location. These unfavorable weather conditions might have contributed to the difference in yield and yield components and NUE. In part, environmental variation observed in this study can be explained by the different soil types, residual soil N characteristics therein. For example, the Manhattan

(Unit 7) site has history of sorghum–soybean rotation while the Manhattan (Unit 1) was on sorghum–sorghum rotation and the soils are sandy and would be expected to display low N mineralization capabilities. The cropping system in Ottawa was maize–sorghum rotation in 2010 and maize–soybean in 2011, while in Hays it was fallow for three years.

4. 2 Phenology

The study shows variability among genotypes (hybrids and inbred lines) and within the types in all the traits that were measured. Flowering duration among the genotypes ranged from 55 d – 75 d after planting averaged across the all environments for both years. Flowering duration in 2011 occurred at a period of long dry spell and high temperatures, which were not favorable for seed set and grain filling. Yield variability of grain crops especially grain sorghum is often related to environmental conditions during the most sensitive stages of crop development (Gross and Kigel, 1994; Wheeler et al., 2000). Prasad et al. (2001) and Prasad et al. (2008) reported that, reproductive processes in sorghum that occur during flowering, such as pollen production, pollen germination, pollen tube growth, fertilization, and seed set, at temperature > 32°C are highly sensitive to high temperature stress. Short episodes, 10 d before flowering or at flowering of high temperature stress (38°/22°C) can cause significant yield reductions in sorghum. The most sensitive stages during reproduction stage of crop development in sorghum have been researched by (Prasad et al. 2008).

Application of N fertilizer resulted in a decrease of number of days to flowering by 3 d. Other researchers have reported similar effect on N promoting early flowering in sorghum (Kamoshita et al., 1998; Buah et al., 2009). Based on the number of days to maturity the genotypes used for the study could be classified early (100 – 110 d), medium

(111 – 120 d) and late (121 – 131 d) maturing (Table 2). The late maturing genotypes were mostly the inbred lines and hybrid 98840. The late maturing hybrid was one of the top yielder among the genotypes because it was able to escape the high temperatures during flowering time especially in 2011 and had enough time to accumulate more biomass, which was eventually converted into grain.

4. 3 Physiological Traits

Significant differences in average chlorophyll meter readings across locations, growth stages, and among genotypes was observed. This finding is in agreement with other researchers (Schepers et al., 1992; Sunderman and Lamm, 1991; Mutava et al., 2011) who have all reported significant variation among grain sorghum genotypes for chlorophyll content. Piekielek and Fox (1992) reported SPAD meter readings in sorghum that ranged from 11.5 to 59.6 across locations and genotypes. There variability observed in our study could be explained by factors such as plant stress from other nutrient deficiencies or from disease, insect damage, or cold temperatures. For instance, on soils with marginal N availability and cultural practices could lead to differences in leaf chlorophyll levels of individual plants without corresponding differences in field yield. Nitrogen fertilizer applied to the field before sampling or high rates of N fertilizer applied at planting could temporarily compensate for low soil N availability and raise the chlorophyll levels at sampling (Piekielek and Fox, 1992). Follett et al. (1992) also reported that factors such as location, moisture and soil N and cultivar differences may have an effect on leaf greenness and resultant chlorophyll meter readings. Generally, the inbred lines, especially the stay green genotypes were superior to the other genotypes for SPAD in 2010. This was not the case in 2011 due to the high temperatures. The stay

green trait in sorghum helps the plant maintain its chlorophyll for a longer period during maturity. Thus, providing longer supply of photosynthates during the seed filling duration, as there is a constant supply of resources from the leaves resulting in higher yields. However, a decline in chlorophyll content in stressed plants could lead to the inability of the plants to take up adequate nutrients from the soil due to limited soil moisture and therefore a depletion of the available photosynthates in the leaves, mainly nitrogen, which leads to decline in chlorophyll content. This could also explain the difference observed among the genotypes in 2011.

The difference in the SPAD readings observed among the genotypes does not necessary translate to improved carbon exchange rates (Maranville and Madharan, 2002). Mutava et al. (2011) evaluated SPAD data for sorghum under field conditions and found difference among genotypes however; correlation of SPAD readings to grain yields was poor. This concurs with our findings where correlation with SPAD and grain was weak. One possible cause of this could be due to the variability among the genotypes that were used for the study. Contradicting these reports are Edmisten et al. (1992) and Wood et al. (1992) both reported that, SPAD readings and chlorophyll measurements was good in predicting grain yield.

SPAD readings gradually increased with increasing N fertilizer rate (Table 4 through 10). The possible explanation could be that, as available N increases, more leaf chlorophyll is produced and the plant displays increasingly greener leaves. The zero N treatment relied on residual soil N supply, which may be limited as the season progressed and the plant requirement for N increased. This explains the differences in leaf chlorophyll content observed between 45 kg N ha^{-1} and 90 kg N ha^{-1} relative to the no

inorganic N fertilizer plots. The G x N observed for SPAD indicated that changes in leaf chlorophyll with N rate differed among genotypes.

Chlorophyll *a* fluorescence (Fv/Fm) was significantly different at various times of crop development (vegetative and maturity) among the genotypes (Tables 4 through 10). Chlorophyll *a* fluorescence provides a non–destructive, rapid means of assessing photo–chemical quantum yield (Krause and Weis, 1991). Plant photosynthetic performance with optimal values of around 0.83 have been measured for most plant species (Johnson et al., 1993). Values lower than this will be seen when the plant has been exposed to stress. In our study, at all the growth stages, Fv/Fm values were less than 0.83, an indication that the plant might have been stressed during the crop growing season. The possible explanation of the low Fv/Fm values observed in our study might be due to the high temperature (> 32°C) coupled with less precipitation during the growing season especially in 2011. Higher temperatures are known to decrease Fv/Fm in sorghum (Prasad et al., 2008) and wheat (Ristic et al., 2007).

4. 4 Growth Traits

No significant difference in total leaf number were observed among N rates, indications that the number of leaves produced by sorghum plant is not affected by N levels. There was no significant interaction between N rate and genotypes for total number of leaves an indication that all the genotypes perform in a similar pattern in all the locations in both years. The results further demonstrated that, there was genotypic effect on percentage leaf senescence. Besides, difference among genotypes to escape from stress which resulted in difference in grain number or grain growth under grain filling stress and consequently in the amount of N translocated from the leaves affect leaf

senescence in anticipated ways. Senescence is normally characterized by chlorophyll loss and a progressive decline in photosynthetic capacity. This could also explain higher percentage (51%) in the leaves senescence in 2011 compared to 2010 (45%). However, the interaction between genotypes and nitrogen regime observed meant the changes in percentage leaves senescence with N rate differed among genotypes. During the growth and development of cereal plants, vegetative tissue first acts as a sink for N and later as a source when N is released from senescing plant parts and is moved to the developing grain. Since the N compounds removed from the leaves cannot be replaced entirely by N absorbed by the roots, the leaf will lose much of its synthetic function, and the lower leaves will senesce. This could also explain the high percentage leave senescence that has been detected in the 0 kg N ha^{-1} treatment plots.

Results from our study have further showed that, there was significant difference in total biomass across the three growth stage (vegetative, flowering and maturity) locations and year (Table 11 through 17). There was corresponding increase in biomass at stage 3 through stage 9. Besides, the large significant biomass produced in 2010 as compared to 2011 was due to the milder (≤ 32°C) weather condition in 2010 which was more favorable for plant growth. Location difference was due to soil profile N, cropping history and moisture difference. It is worth mentioning that, sampling times during the growing season could also contribute to difference in total biomass. Hybrids as a group produced more aboveground biomass than the inbred lines. Results from our study revealed that maximum biomass was obtained at optimum recommended rate, followed by half recommended rate and the least at the no inorganic N. Zhao et al. (2005) reported that N deficiency in grain sorghum caused reduced leaf area, reduced chlorophyll and

photosynthetic rate resulting in lower biomass production. However, according to Heitholt et al. (1991), N deficiency in crops reduces ribulose 1-5 biphosphate carboxylase/oxygenase (Rubisco) activity. Maranville and Madhavav (2002) reported that phosphoenolpyruvate carboxylase (PEPcase) and Rubisco activity in sorghum leaf was reduced by N deficiency which reduced biomass production. Thus, the low amount of biomass obtained under the no inorganic N fertilizer could be due to N deficiency.

4. 5 Yield and Yield Components

The study also demonstrated grain yield and components of yield was generally better in 2010 than in 2011 averaged across all environments. For site year, the hybrids generally performed better than the inbred lines. Yield of the hybrids were 31% greater than the inbred lines. The better yield of the hybrids was manifested in both seed numbers and seed size averaged across locations and years. This is obvious because the hybrids have already gone through some improvement for higher yields as compare to the lines, which are purposely use for breeding programs. Contrast to low yields of the inbred lines, genotypes Tx2783 and Tx7000 both non–stay green lines were comparative to hybrids for grain yield especially in environment of high residual N (Tables 1). The potential exhibited by these genotypes can be exploit as good combiners in future breeding programs. Efficiency of grain production in crop plants is frequently expressed as HI. Sinclair (1998) and Hay (1995) have reported that HI is an important trait associated with the dramatic increased in crop yield that have occurred in the twentieth century. Grain HI reflects the partitioning of photosynthetic between the grain and the vegetative part of the plant and improvement in HI emphasize the importance of carbon allocation in grain production. Higher NUE has also been observed in rice varieties with high HI (Bufogle et

al., 1997). The variation found for HI dynamics could be largely explained by difference in assimilation during grain filling and remobilization of pre–anthesis assimilate. Genetic variation for this trait has been reported in different crop types (Slafer and Savin, 1994; Kumudini et al., 2002; Papakosta and Gagianas, 1991; Royo and Blanco, 1999; Bonnett and Incoll, 1993). Contrary, the HI value was not close to the maximum HI of 0.55 that has been reported as a reflection of genetic potential of most current sorghum hybrids (Hammer and Muchow, 1994). This could be to the fact that, the genotypes in our study are not yet been developed to be use for commercial production. There difference in grain yield manifested through difference in total biomass and HI can be explained using the source–sink framework during grain filling and remobilization of pre−anthesis assimilates (Gerner and Hans, 1994). The difference in total biomass at maturity among the genotypes in this study and hence the major difference in the yield may be explained predominantly by difference in assimilates during grain filling period.

Drought occurrence in relation to anthesis stage causes a drastic reduction in yield and yield components. (Papakosta and Gagianas, 1991; Blum et al., 1994; Araus et al., 2002; Borras et al., 2002; Hammer and Broad, 2003; Seghatoleslami et al., 2008). Crops depend on remobilization of stored carbohydrates from pre–anthesis stage when drought stress occurs during grain filling. This becomes more important under terminal drought stress that is coincident with grain filling period and inhibits current photosynthesis. This could be a possible explanation of the yield advantage of 2010 over 2011. Seed numbers (m^{-2}), 200 kernel weight and harvest index were all affected by temperature stress. High temperature stress can directly affect seed yield by influencing seed−filling duration and rate, both of which are highly sensitive to HT stress (Prasad et al., 2006a and b). The

variability of the seed size observed in this current study might be due to decrease seed filling duration as result of the high temperatures (> 32°C) during the growing season especially in 2011. Despite the fact that environmental conditions were favorable at the time of flowering, but stress occurring 10 – 15 d before flowering, has the tendency to reduce seed numbers. This condition prevailed in 2011. Thus, seed numbers may be reduced if drought stress occurs immediately after seed set because of embryo abortion. As indicated in the results, 2011 was a dry year and this resulted in a reduction of seed numbers, 200 kernel weight and harvest index for most of the genotypes. The strong correlation seen in this current study between grain yield and grain number concurs with observations made by Bidinger and Raju (2000) in pearl millet (*Pennisetum glaucum* (L.) R. Br.). Also Mutava et al. (2011) found a strong correlation between grain yield and HI, this concur with our findings in this current study.

Nitrogen regimes were seemed to increase yield and yield component across the locations, genotypes and years. There were instances when half recommended rate was comparative to optimum N regimes. Thus, in such situation, it will be prudent to use the half recommended rate to reduce production cost. Variable response to the application on N fertilizer have been observed in sorghum (Muchow, 1990) owning to climatic, soil and genotypic factors across seasons and locations. Part of this yield variation is associated with difference in the capacity of the soil to supply N and in the efficiency of recovery of applied N fertilizer. The other component contributing to variable yield response to fertilizer N is the N requirement for yield determination. The N requirement is dependent on yield expectation in a given environment as determined by climatic management and cultivar. Non–significant interactions between genotypes and N levels for most of the

yield and yield components and uptakes parameter suggested that sorghum genotypes could be evaluated for N use efficiency at a single N level.

4. 6 NUE and Components of N Use

Many studies have reported variation for NUE and components of NUE at high and low N inputs (Gilteson et al. 1998, Sinebo et al., 2004) as well as significant effect of genotype and N fertilization (Le Gouis et al., 2000; Chardon et al., 2010). In our study NUE and components of NUE were significant, influenced environments where soil test results show low residual N (Table 1).

The results indicated that there was genotypic difference in N uptake in plant parts (leaves, stems and grain) (Tables 25 – 32). In both years, higher amount on N was translocated from the soil to the leaves relative to the stem at flowering stage but more N was mobilized from the leaves and stems to the grain at maturity. Among the genotypes the hybrids tended to take up more N than the inbred lines. This agrees with findings of Nakamura et al. (2002) that N absorption was regulated by root activities and was higher in hybrids than in local varieties or inbred lines in low–N conditions among grain sorghum genotypes. Greater N accumulation in the grain was associated with higher grain yields and NUE. In our study, it was observed that much of the N was taken up at flowering and remobilized to the grain which contributed to the N protein deposition in the grain. Average across the genotypes and sites, grain N accumulation was greater than in the leaves and stems. During the grain filling stage, it is the N accumulated in leaves and stems before flowering that is in large part remobilized to the grain and that contributes to grain N protein deposition (Mae, 1997). This could explain the higher N in the grain than the other plant parts that have been observed in our study. Nutrient uptake

by sorghum is influenced by several factors including nutrient availability, soil water availability, soil organic matter, soil chemical and physical properties, type of previous crop, plant population and the genotype (Wortmann, 2007). This could explain the genotypic difference in the N uptake that has been observed in this current study. Besides, N uptake was greater in environment with greater grain and total biomass yield indicating that total N uptake was largely a function of dry matter production rather than grain and stover N. Although we did not study root growth, Rao et al. (1991) and Lee et al. (1996) indicated that fertilizer N can increase N availability from other N pool and /or stimulate root growth and N uptake. Increasing N regimes caused a corresponding increase in N concentration in plant parts when averaged across the genotypes and locations for both years. This is in agreement with Eghball and Maranville (1993) who found that the mean N influx of maize increased with increasing soil N supply. It was also evident that the hybrids in this current study contained more plant N than the inbred lines at both flowering and physiological maturity. This is partly of the high biomass and grain yield production potential of the hybrids. This concur with findings of Dhugga and Waines (1989) who have showed that, genotypes with high yield potential accumulated more N than genotypes with less yield potential.

The results further demonstrated difference in NUE and component of N use across locations and years. Significant G x N was observed in environment with low soil residual N for NUE and components of N use in 2010, an indication that the change in NUE with N rate differed among genotypes. The possible cause of non–responsive of the genotypes to N was due to the high residual N at the time of planting in 2010 in Manhattan and 2011 in Ottawa (Table 1). In both environments, NUE decreased linearly

with increase in N rate. The reduction in NUE with applied N is consistent with what was reported in previous studies (Wani et al., 1990; Buah et al., 1998; Maman, 1999; Wortmann et al., 2007). This relationship generally occurs because plant N content increase proportionally more than dry matter production with increase fertility levels. This observation seem to confirm the explanation that plant population occurring at relatively N poor sites are adapted to these environment by either phenotypically or genetically increased efficiency of N use.

Besides, difference in NUE may be related to many physiological processes such as absorption, nitrate reduction efficiency, N remobilization, translocation assimilation and stockage (Isfan, 1993). As N rate increased, the amount of N relocated from biomass to grain increased in both 2010 and 2011. The amount of N relocated from biomass to grain averaged across both years ranged between 15.1% to 53.4% for Ottawa compared to 26.2% to 48.2% in Manhattan (Unit 7) (Tables 25 – 32). Genotypes with the highest yield generally had greater NUE values, which agree with the results of Onken et al. (1985) and Gardner et al. (1994). The NUE values were also greater in 2010 than in 2011 reflecting the overall higher grain yields in that year.

The quadratic response of N on some of the parameters computed indicated that either maximum uptake had been achieved, that other nutrients deficiencies may have impeded further uptake, or that nutrient imbalances may have occurred with increasing N. In soils with limited available N, utilization efficiency has been found to be more important than uptake efficiency in contributing to genotypic difference in grain production. This agrees with our findings when in 2010 in Ottawa due to the low residual N, utilization efficiency was much higher than that of Manhattan Unit 7. Nitrogen use

efficiency is a combination of N uptake efficiency and N utilization efficiency. Increase of N uptake efficiency and/or N utilization efficiency will lead to an increase of NUE. This could explain the best value of NUE under low nitrogen input. Raun and Johnson (1999) proposed increase N uptake efficiency as strategy to increase NUE. In this current study, N uptake efficiency differed among the genotypes. Crop N uptake is dependent on the available mineral soil N and nitrogen use decreases with lower temperature and soil water status (Muchow, 1999). Nitrogen uptake and metabolism are energy dependent and hence greater photosynthically capacity is required to support higher uptake. Plants flowering late have larger leaf area and possibly deeper roots. Such plants are usually large and have greater capacity for photosynthesis and take up more N. This was observed with the late maturing hybrid (99480) which was superior to the other genotypes for uptake efficiency.

Nitrogen harvest index is a measure of N partitioning in sorghum which provides an indication of how efficiently the plant utilized the acquired N for grain production. Genetic variability for NHI exists within the small grain genotypes and NHI is characteristics of genotypes and these traits may be a useful parameter in selecting sorghum genotypes for higher grain yield. Besides, NHI which represents the increased capacity of the genotype to mobilize and translocate N from the leaves and stem to grain show increasing N concentration with increasing N. This is consistent with other studies in sorghum (Kashimoto et al., 1998) and in maize (Manson and D'croz–Manson, 2002) who have both indicated an improved protein concentration in grain with increasing N.

Differences in fertilizer recovery are the most likely associated in part to difference in root systems (Maranville et al. 2002). This could explain the difference in N

recovery that has been observed in this current study. The relatively low N recovery in 2011 may be attributed to the overall low in–season precipitation. According to Eck and Jones (1990), soil water and in–season precipitation are favorable for higher grain yields and increased response to applied N. Other factors that can be responsible for low N recovery in sorghum are cultivars (Gardner et al., 1994), management system (Sow et al., 1998) and soil available water.

4. 7 Conclusion and Future Activities

In summary, grain sorghum genotypes vary in their response to nitrogen fertilizer. There was a significant difference in NUE and components of N efficiency in sorghum hybrids and inbred lines. Besides, there was a significant difference in physiological traits (leaf chlorophyll content and chlorophyll *a* fluorescences) among the genotypes. Grain yield was significant different across all the locations in both years. The maximum grain yield and biomass was obtained at the optimum N regime, followed by the half–recommended rate and the least was no inorganic N. Generally, the hybrids were superior to the inbred lines in all the traits that were measured. Overall, NUE (kg kg^{-1}) ranged from 17.2 – 42.6, utilization efficiency (kg kg^{-1}) ranged from 24.3 – 60.2 and uptake efficiency (%) ranged from 56.1 – 82.5%. Besides, percent fertilizer N recovery ranged from 2.1 – 52.0% and nitrogen harvest index ranged from 43.6 – 81.3%. Overall, the top yielders and high in NUE and component of N use genotypes were 99480 and 26506 both known to be post– flowering drought tolerance. In addition, the low yielding in grain and NUE and components of N use genotypes were B35 and SC35, both known to be stay green.

There were differences in N uptake efficiency among the genotypes used in this current study. An indication of differences in their rooting systems in terms of root length distribution and mass. Besides, low soil fertility, especially P deficiency, is inherent in many soils in West Africa, and Ghana is no exception. Colonization of plant roots by arbuscular mycorrhizal fungi can greatly increase plant uptake of phosphorus and nitrogen. The most prominent contribution of arbuscular mycorrhizal fungi to plant growth is due to uptake of nutrients by extra radical mycorrhizal hyphae. Hence, future potential activities are (1) to evaluate the effect of N fertilizer regimes on root mass and depth among grain sorghum genotypes (inbreds and hybrids) and (2) to evaluate the response of Arbuscular mycorrhizae to P fertilizer regimes among diverse grain sorghum genotypes.

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Figures and Tables

Figure 1. (a) Maximum and (b) minimum temperatures during the growing season at Manhattan, Kansas, 2010 and 2011.

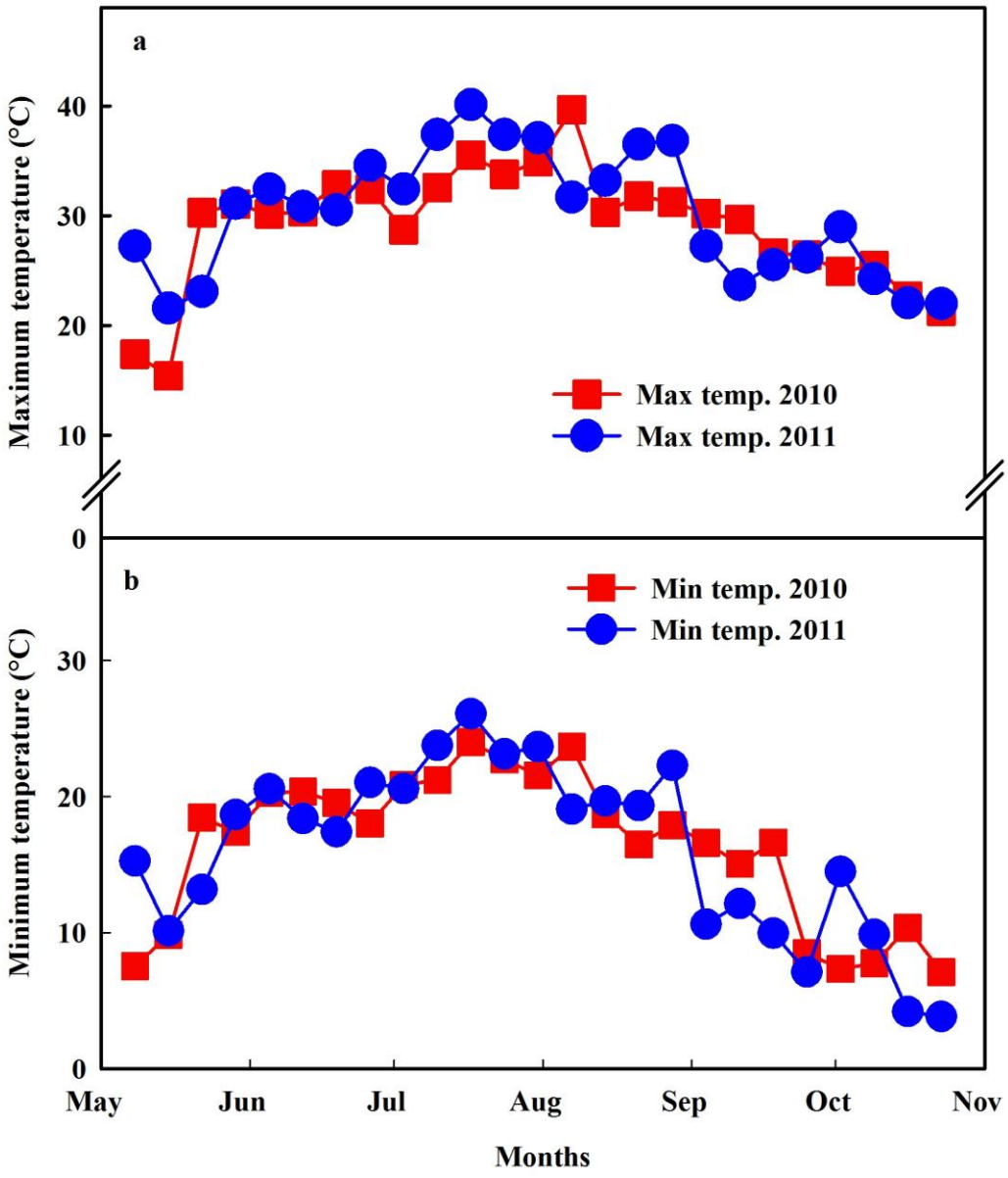

Figure 2**.** (a) Maximum and (b) minimum temperatures during the growing season at Ottawa, Kansas, 2010 and 2011.

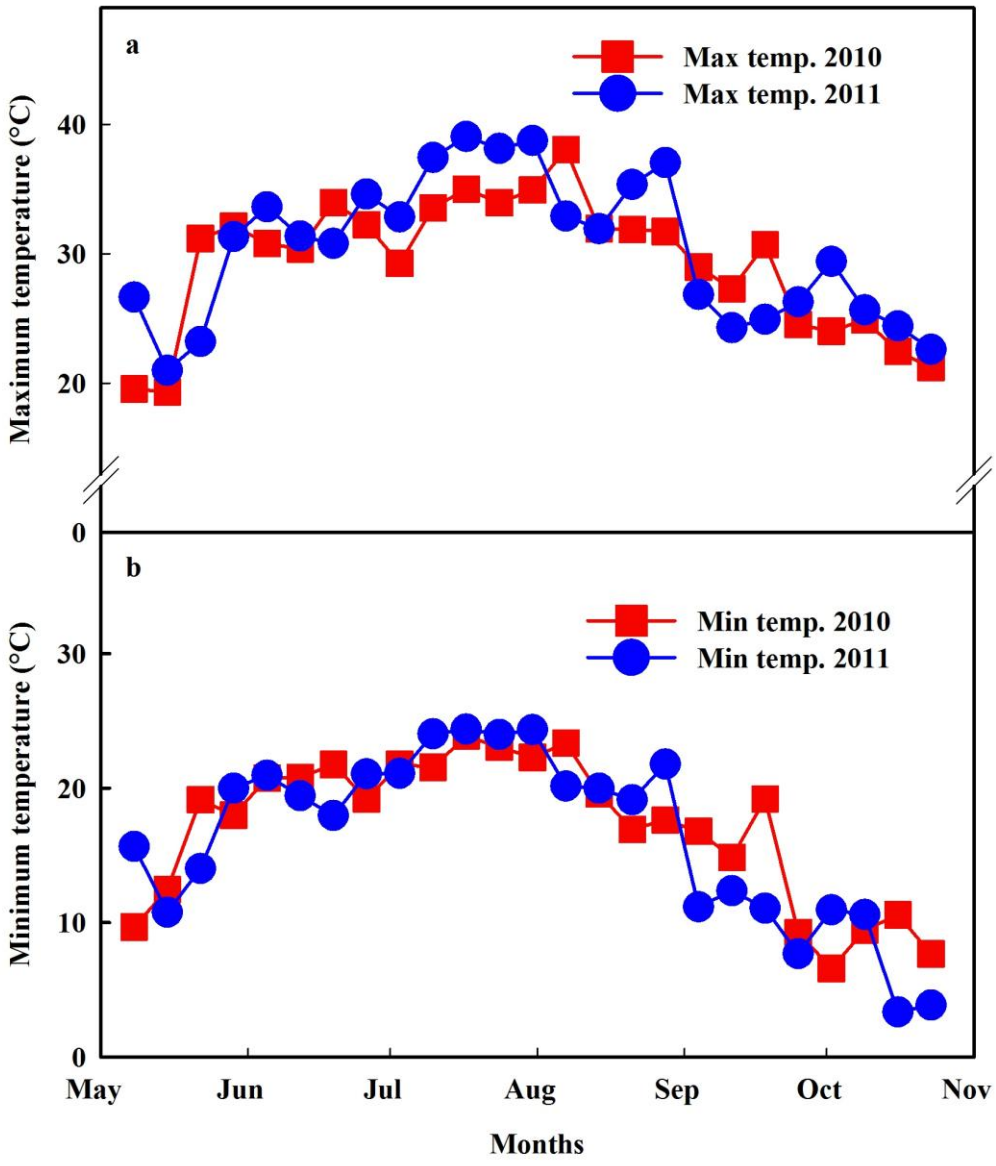

Figure 3**.** (a) Maximum and (b) minimum temperatures during the growing season at Hays, Kansas, 2010.

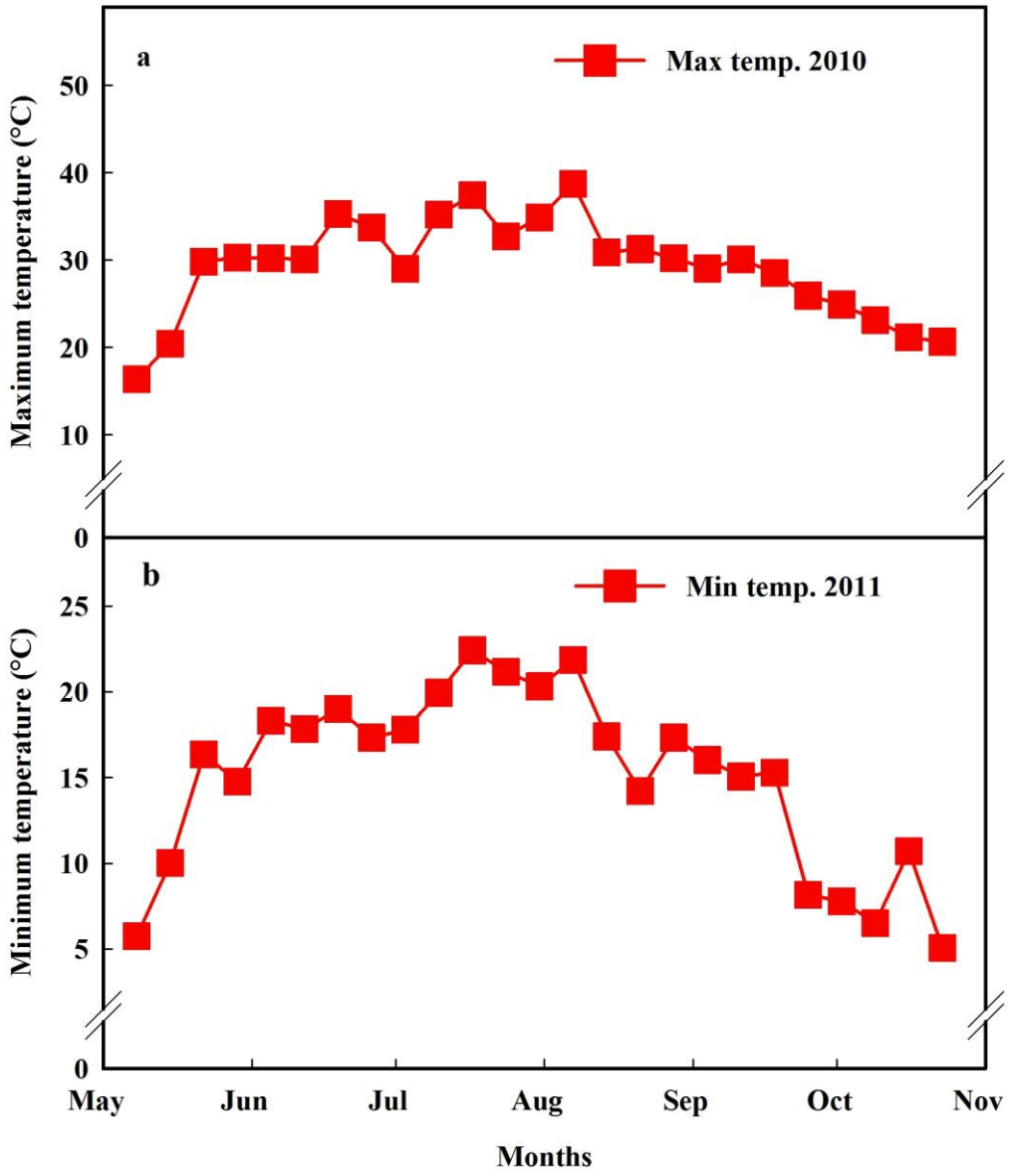

Figure 4. (a) Precipitation and (b) relative humidity during the growing season at Manhattan, Kansas, 2010 and 2011.

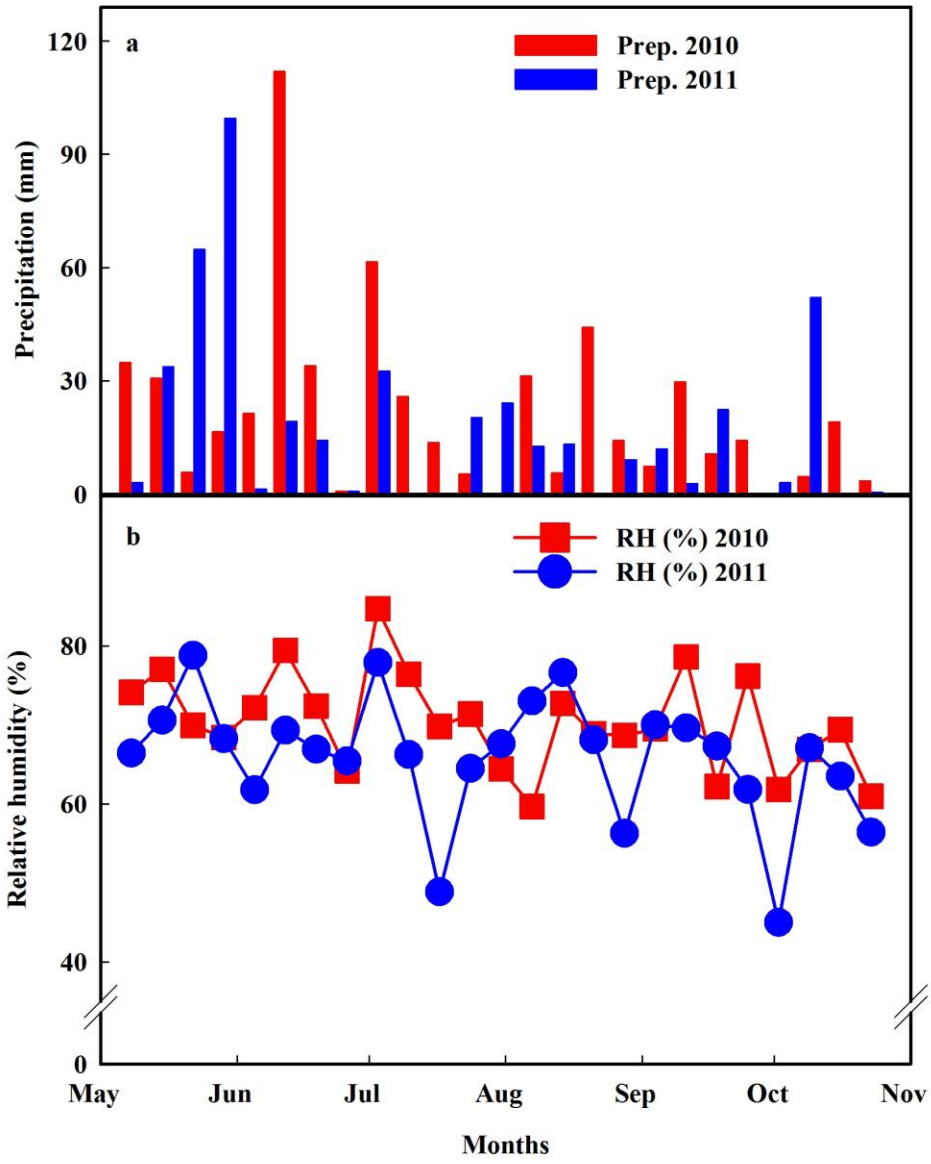

Figure 5. (a) Precipitation and (b) relative humidity during the growing season at Ottawa, Kansas, 2010 and 2011.

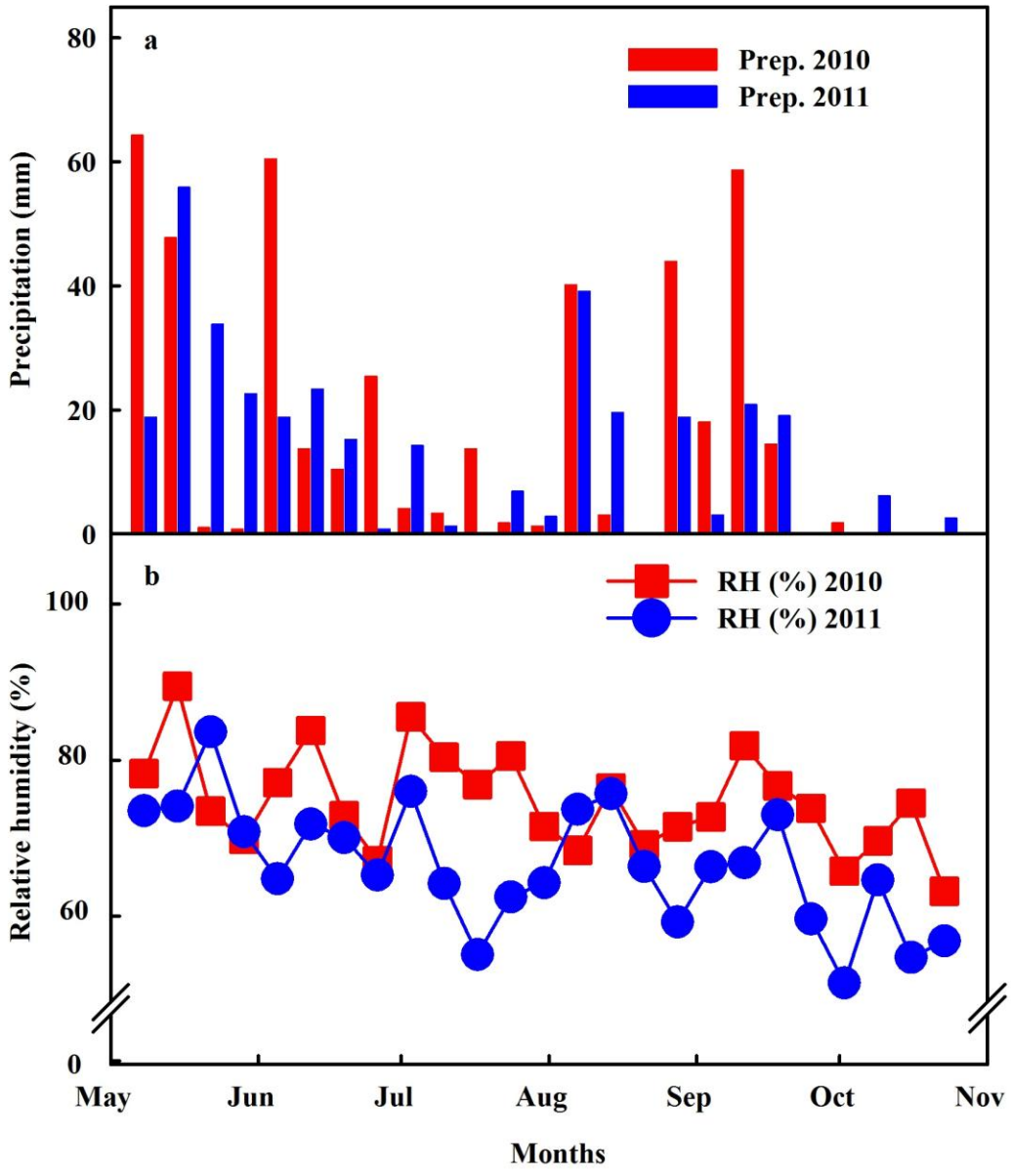

Figure 6. (a) Precipitation and (b) relative humidity during the growing season at Hays, Kansas, 2010.

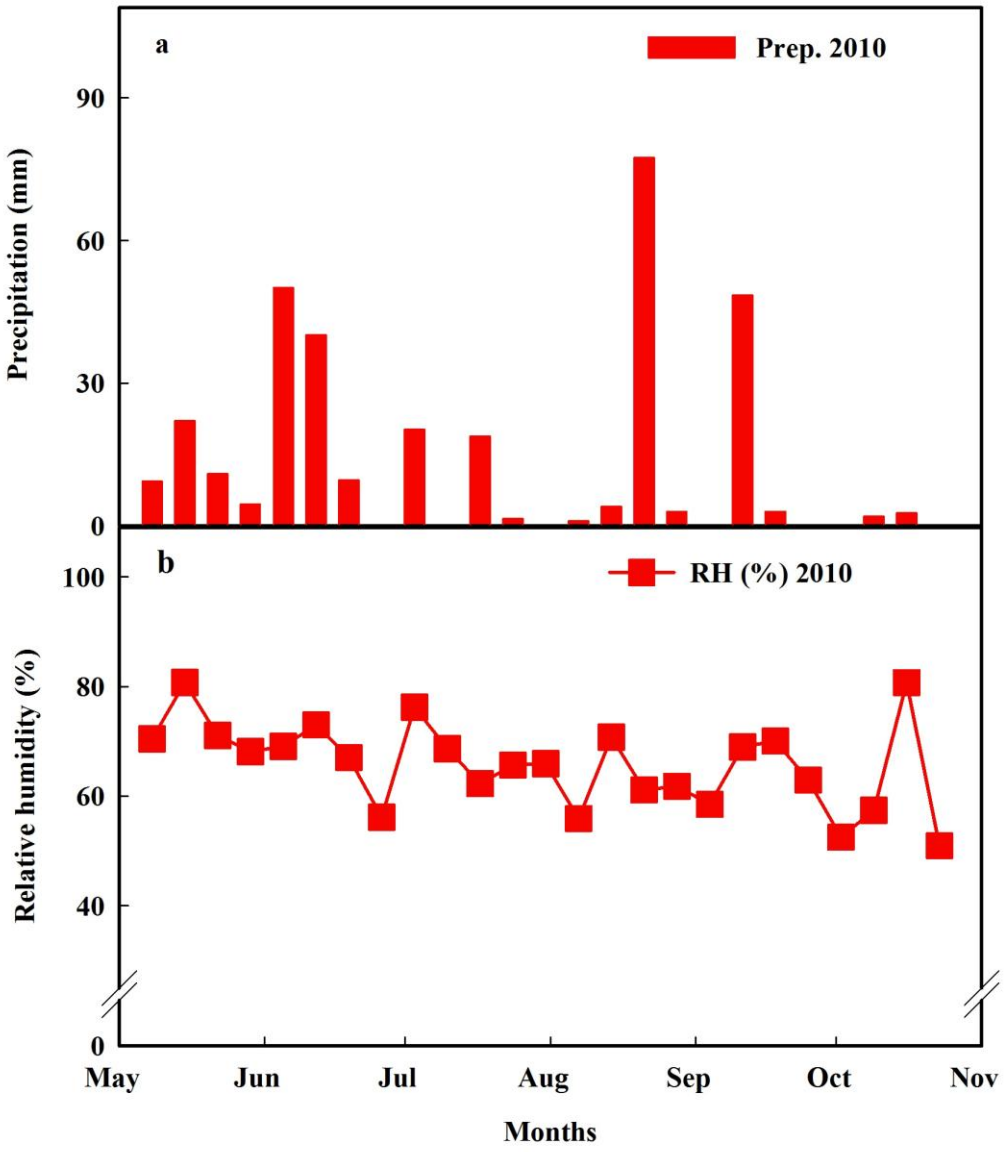

Figure 7. Monthly precipitation (bar) and alfalfa reference evapotranspiration (ET_R) line) at all locations, Kansas, 2010.

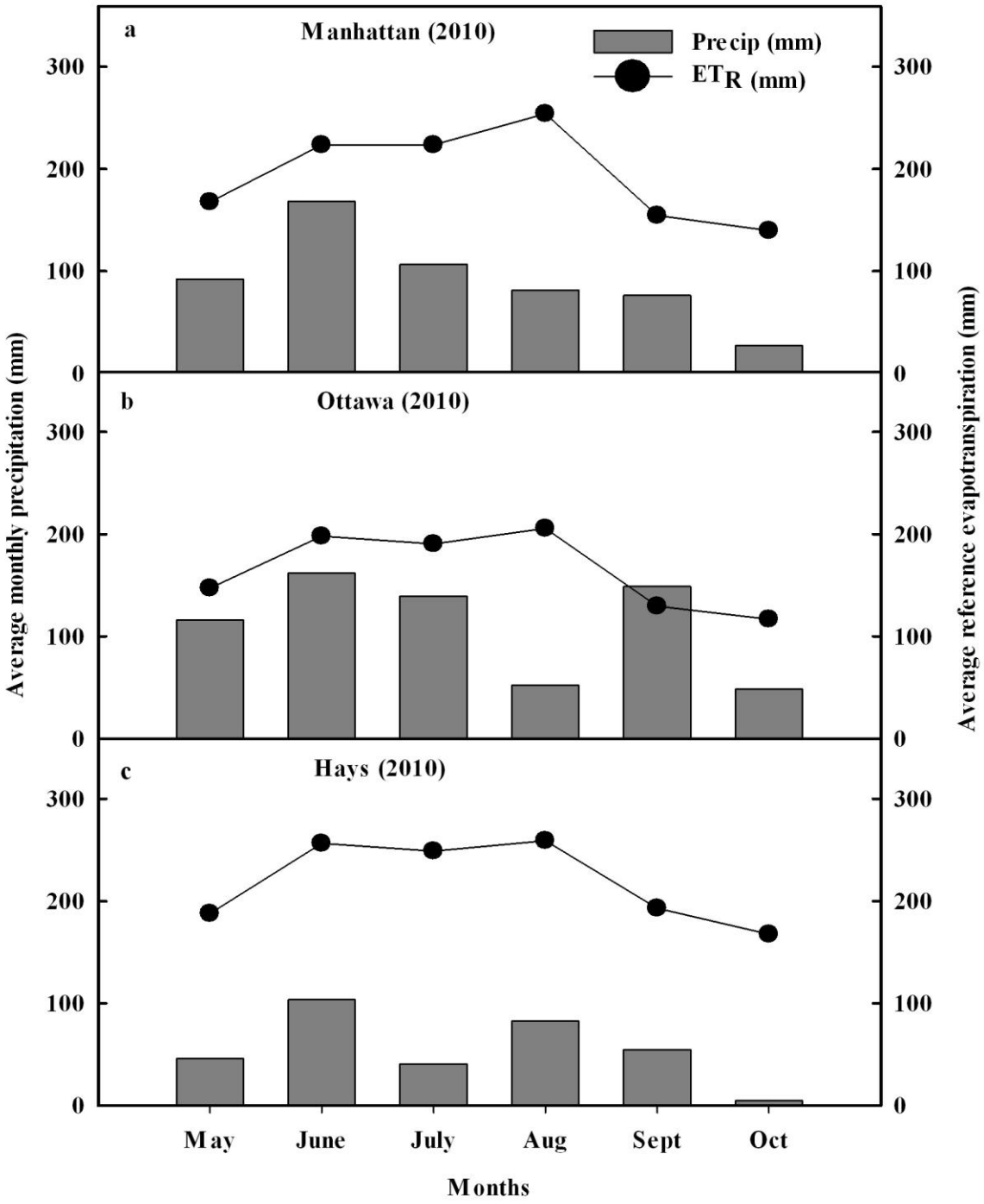

Figure 8. Monthly precipitation (line) and alfalfa reference evapotranspiration (ET_R line) at all locations, Kansas, 2011.

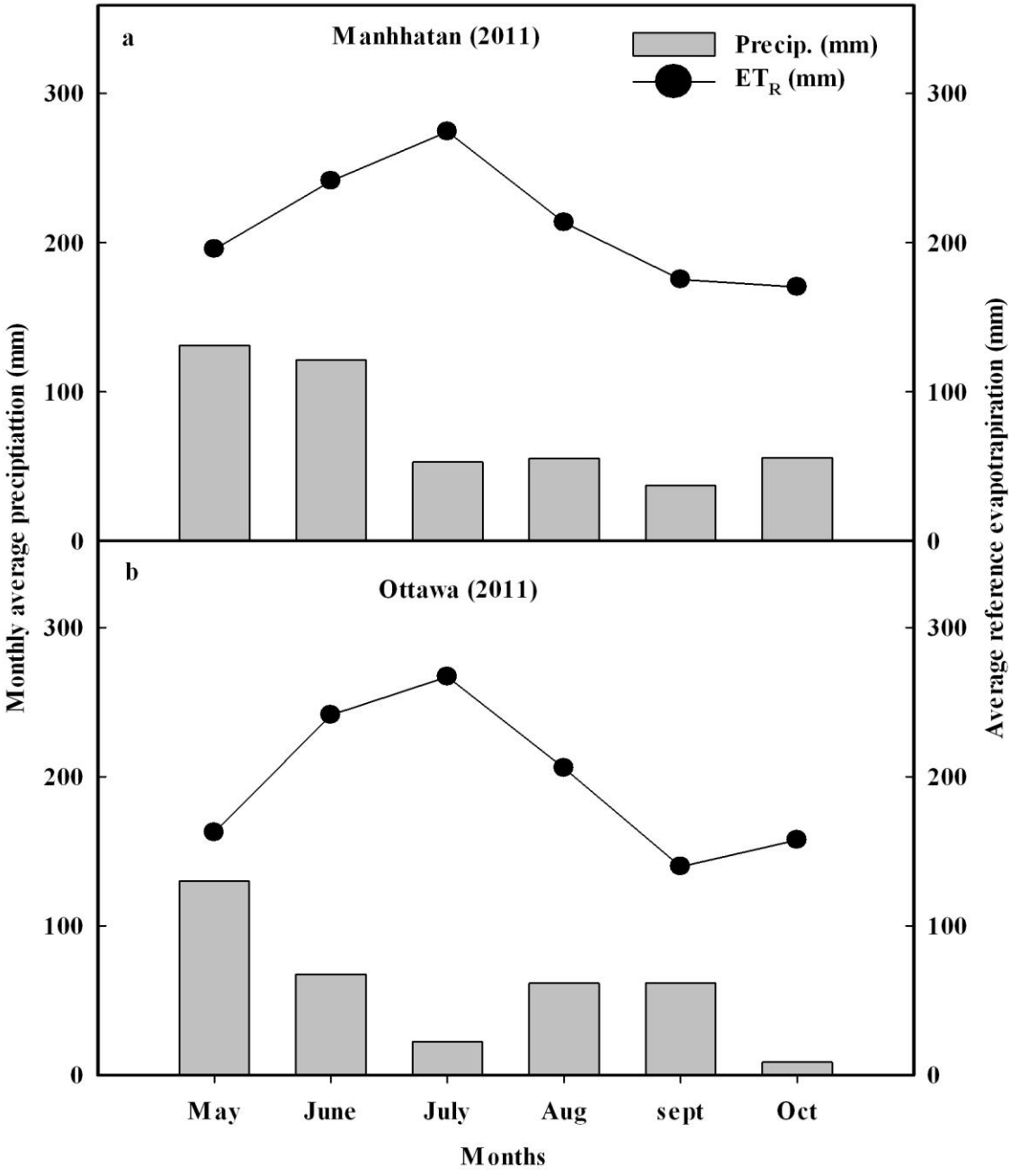

Figure 9. Genotype by nitrogen interaction effect on leaf chlorophyll content at physiological maturity at Manhattan (Unit 1), Kansas, 2010.

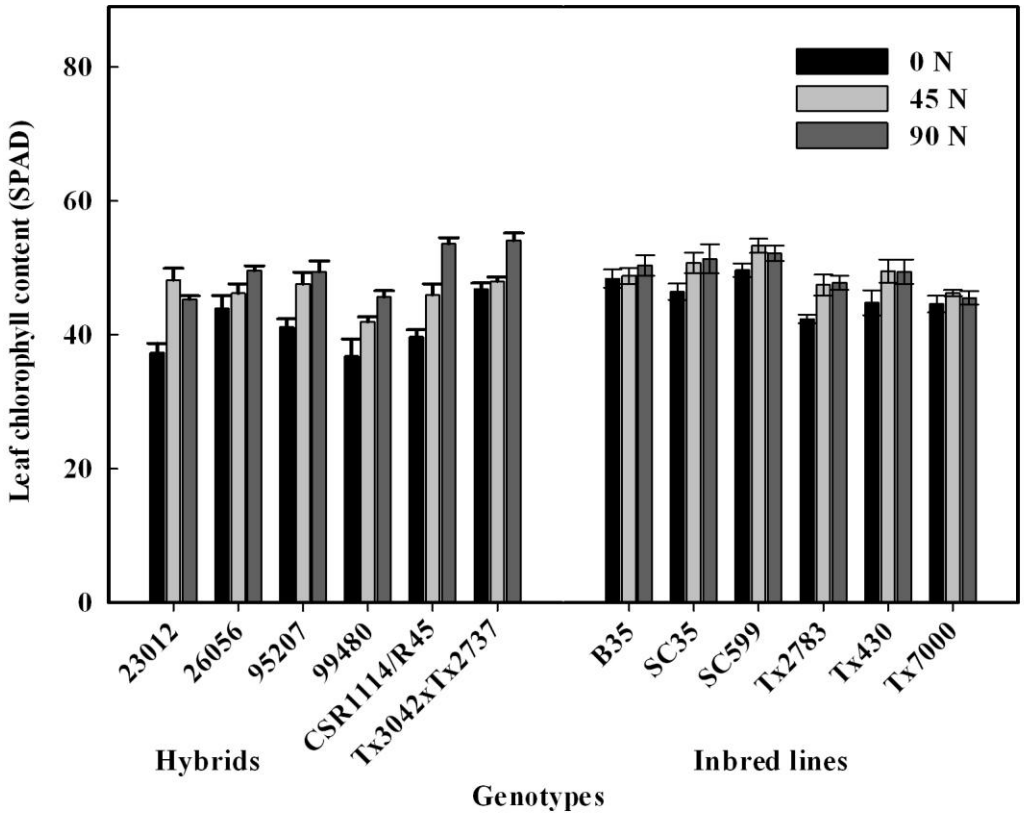

Figure 10. Genotype by nitrogen interaction effect on leaf chlorophyll content at (a) vegetative stage (b) flowering stage and (c) physiological maturity at Manhattan (Unit 7), Kansas, 2010.

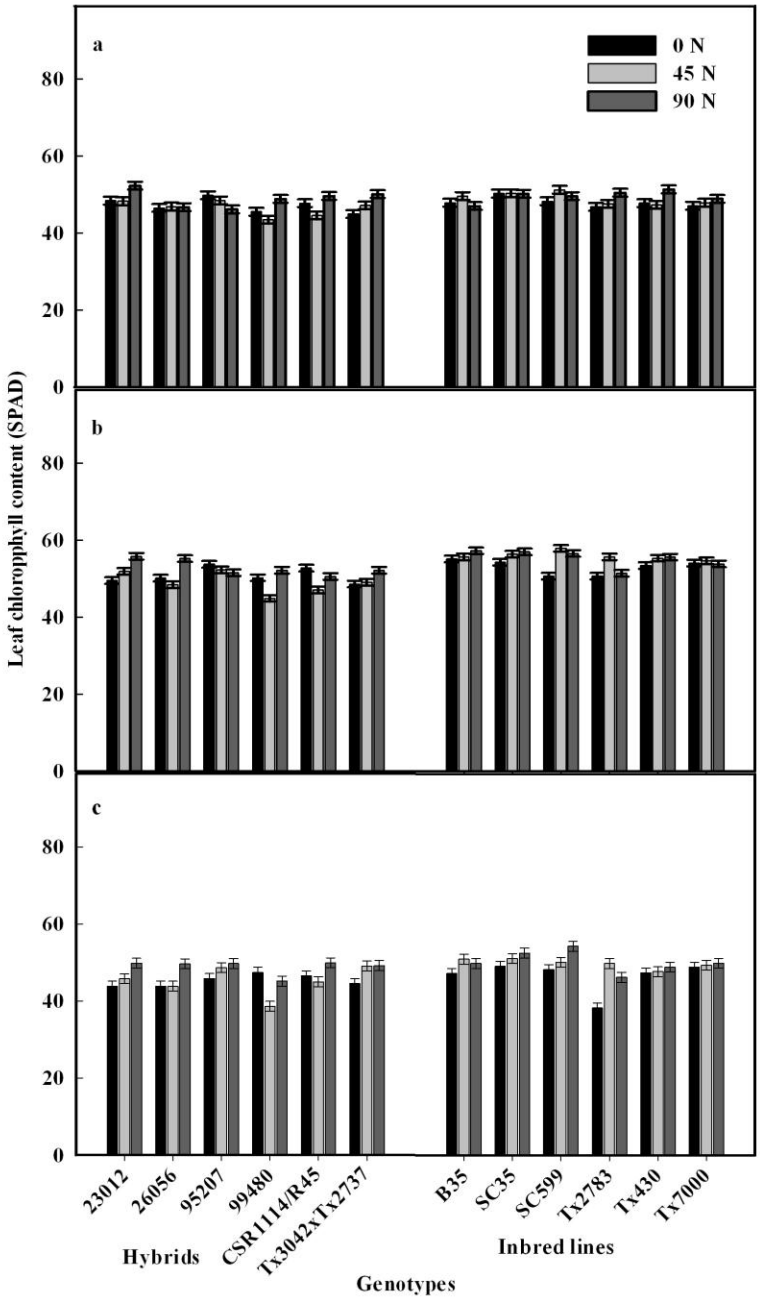

Figure 11. Genotype by nitrogen interaction effect on leaf chlorophyll content at (a) vegetative stage and (b) flowering at Ottawa, Kansas, 2010.

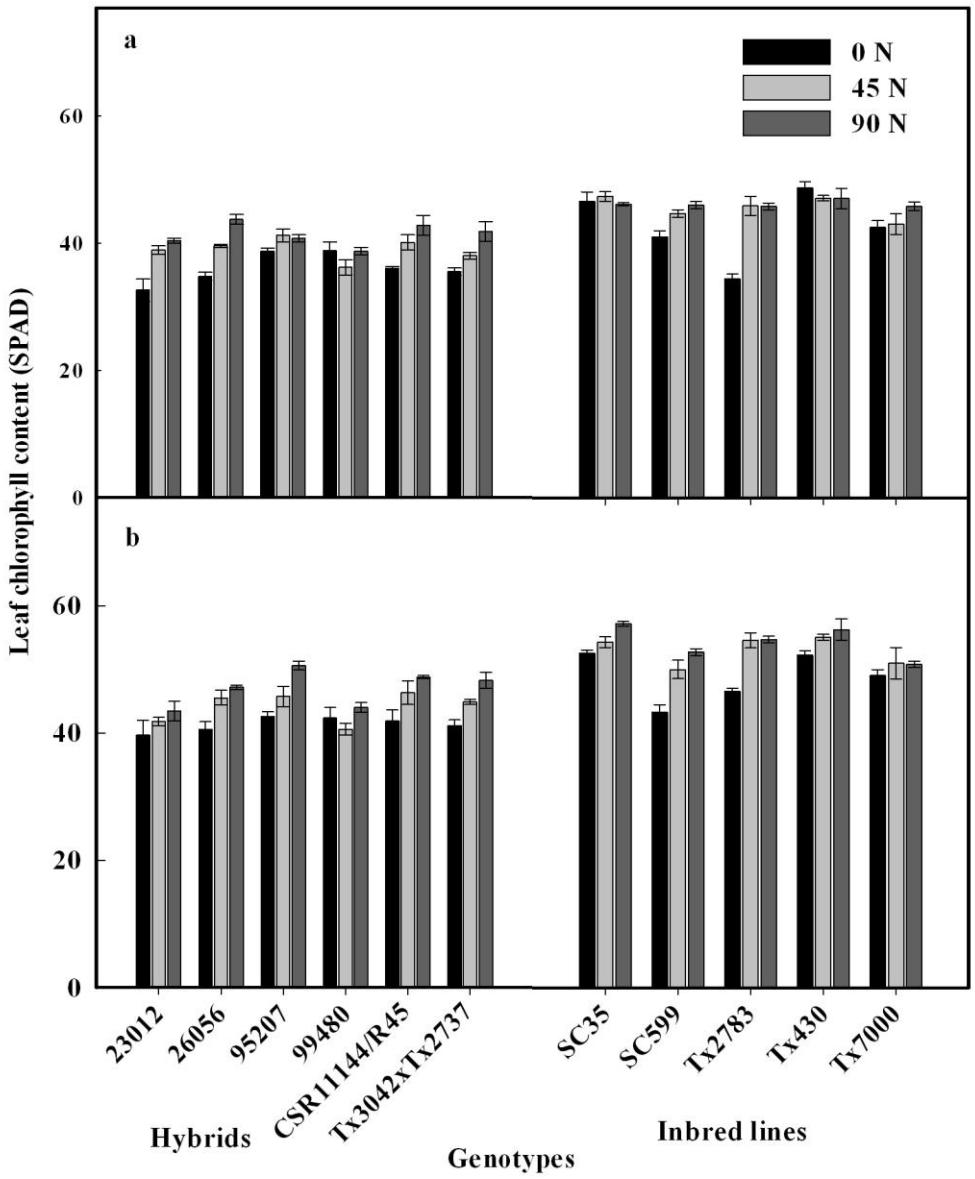

Figure 12. Genotype by nitrogen interaction effect on leaf chlorophyll content at physiological maturity at Hays, Kansas, 2010.

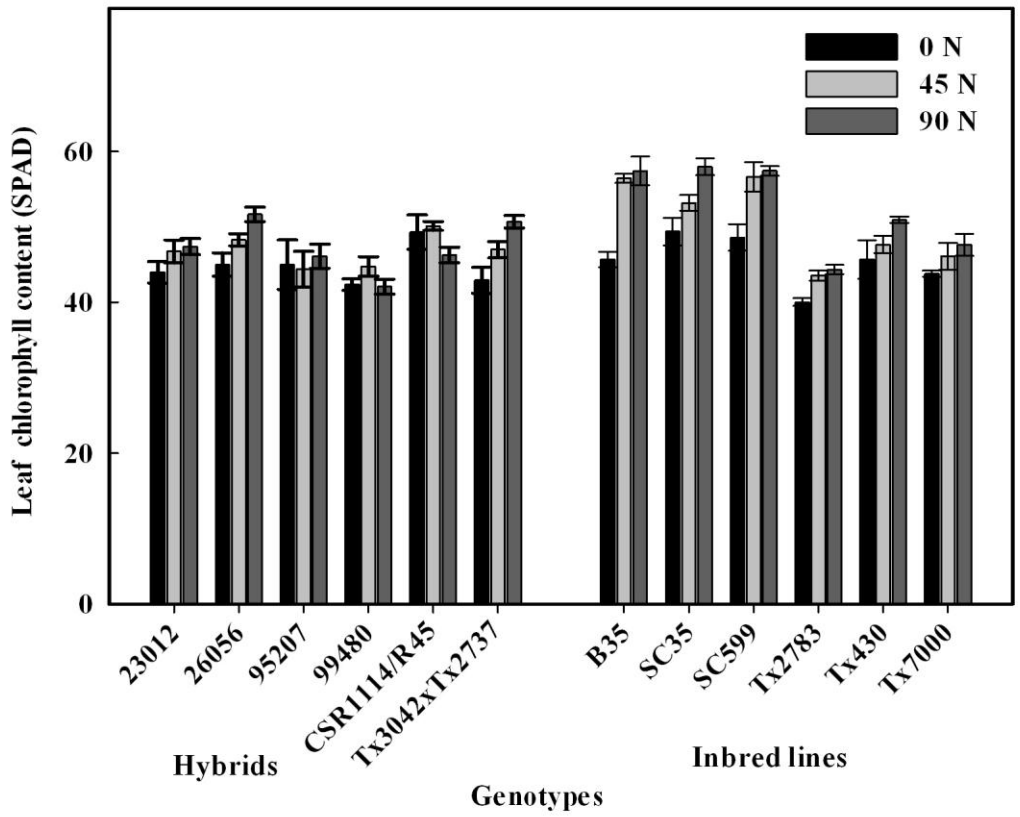

Figure 13. Genotype by nitrogen interaction effect on leaf chlorophyll content at (a) vegetative stage at Manhattan (Unit 7) and (b) physiological maturity at Ottawa, Kansas, 2011.

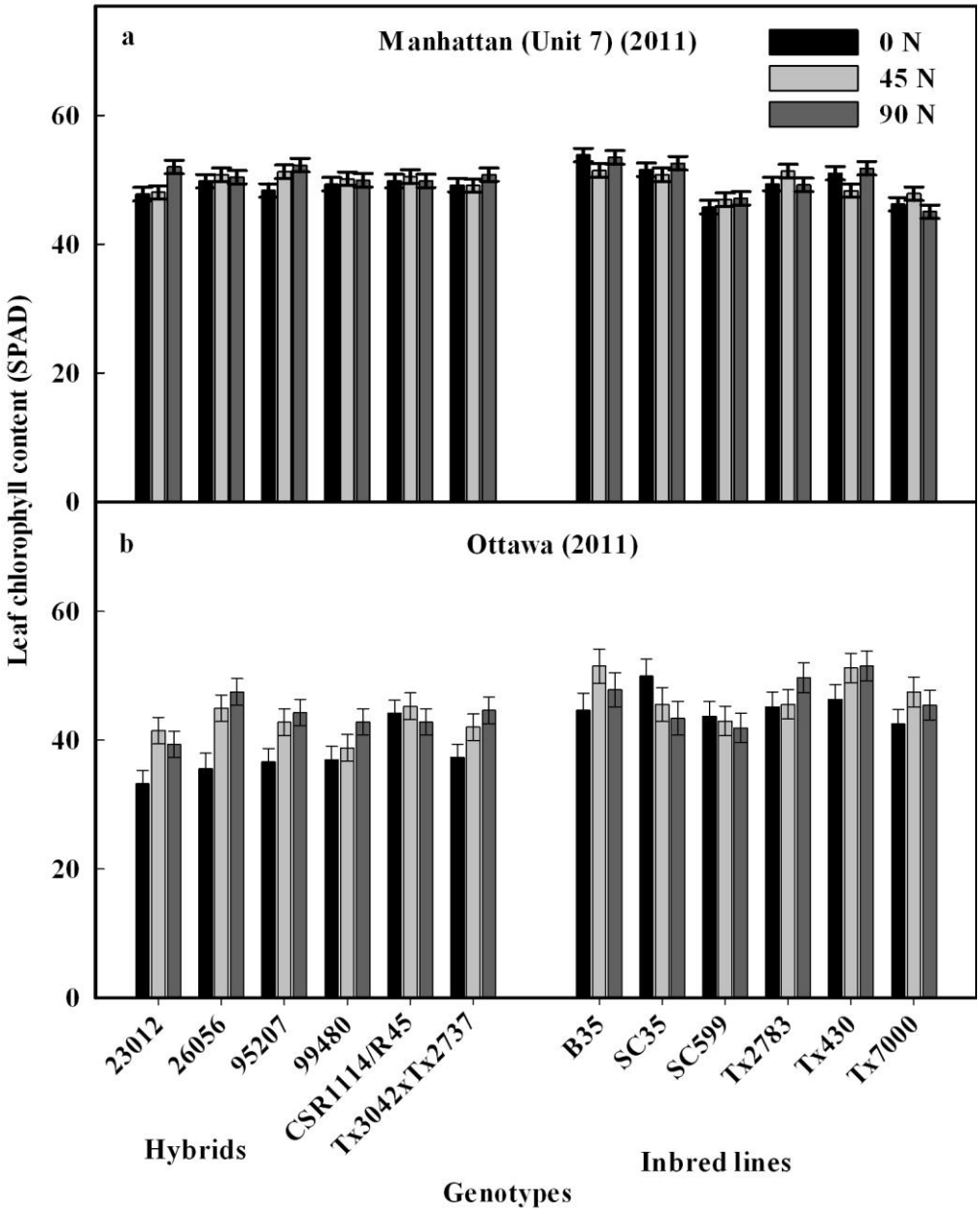

Figure 14. Genotype by nitrogen interaction effect on percentage leaf senesced (a) at Manhattan (Unit 7) and (b) Ottawa, Kansas, 2011.

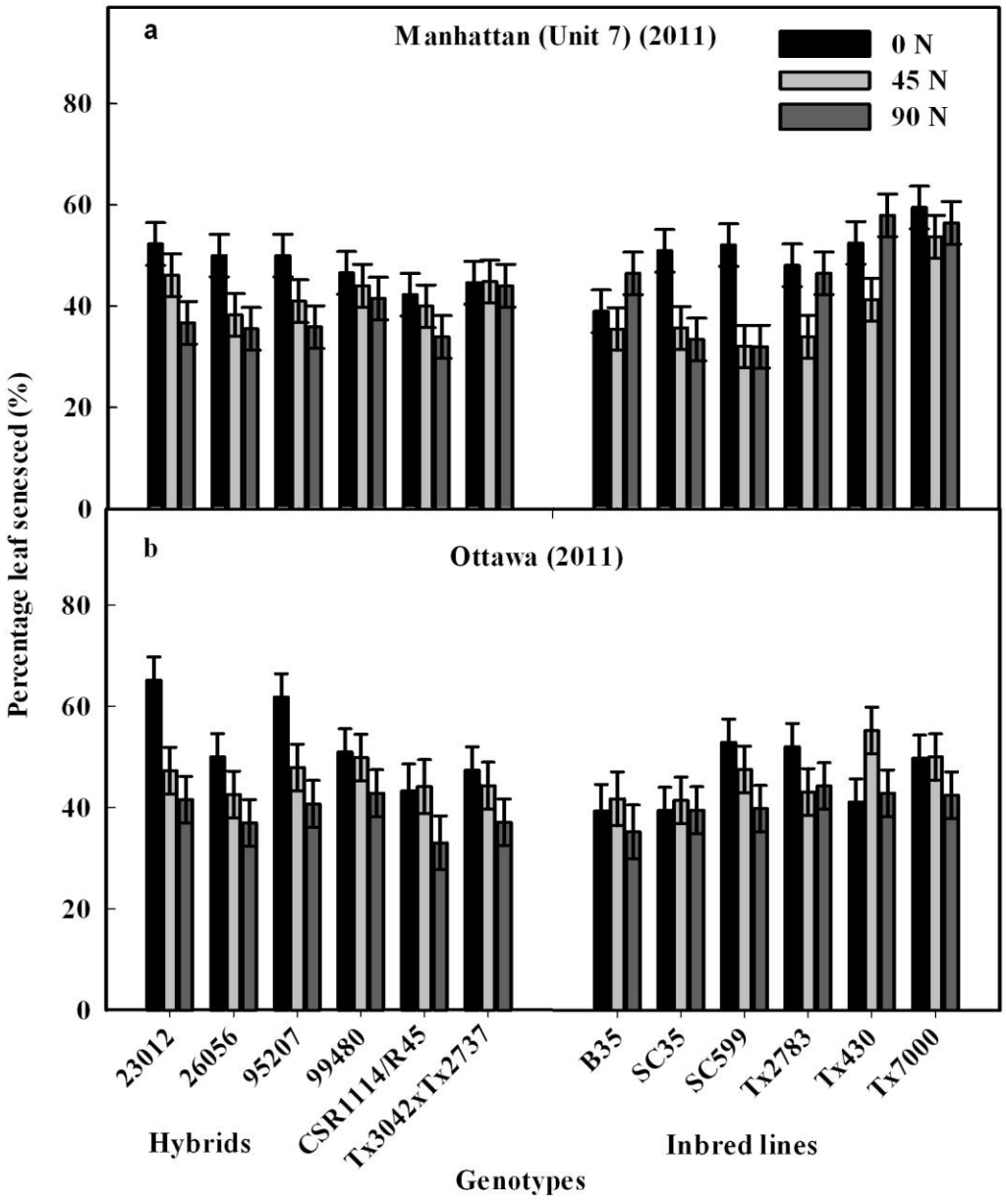

Figure 15. Genotype by nitrogen interaction effect on (a) grain yield and (b) 200 kernel weight at Manhattan (Unit 7), Kansas, 2010.

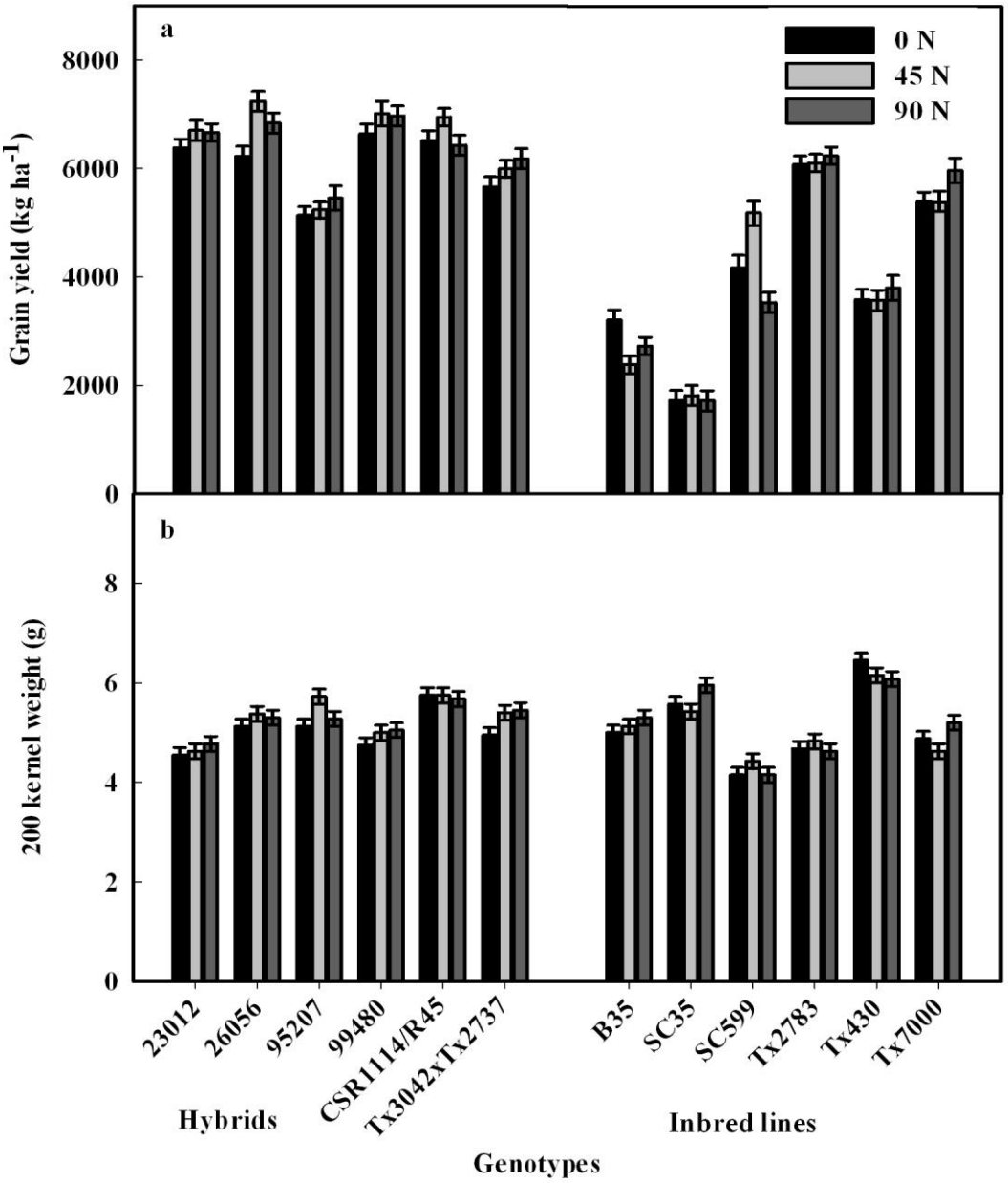

Figure 16. Genotype by nitrogen interaction on (a) grain yield (b) kernel number (m^2) and (c) harvest index at Hays, Kansas, 2010.

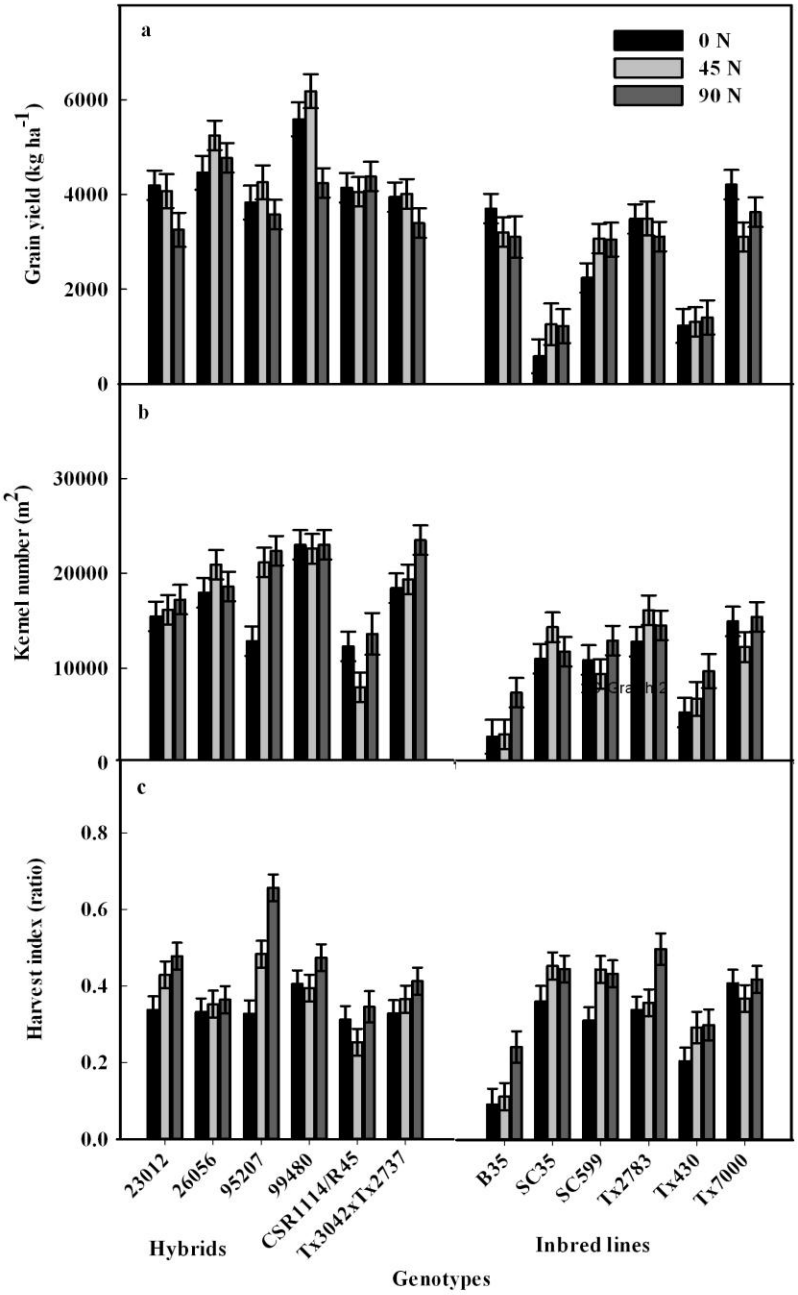

Figure 17. Genotype by nitrogen interaction on (a) grain yield and (b) 200 kernel weight at Manhattan (Unit 1), Kansas, 2011.

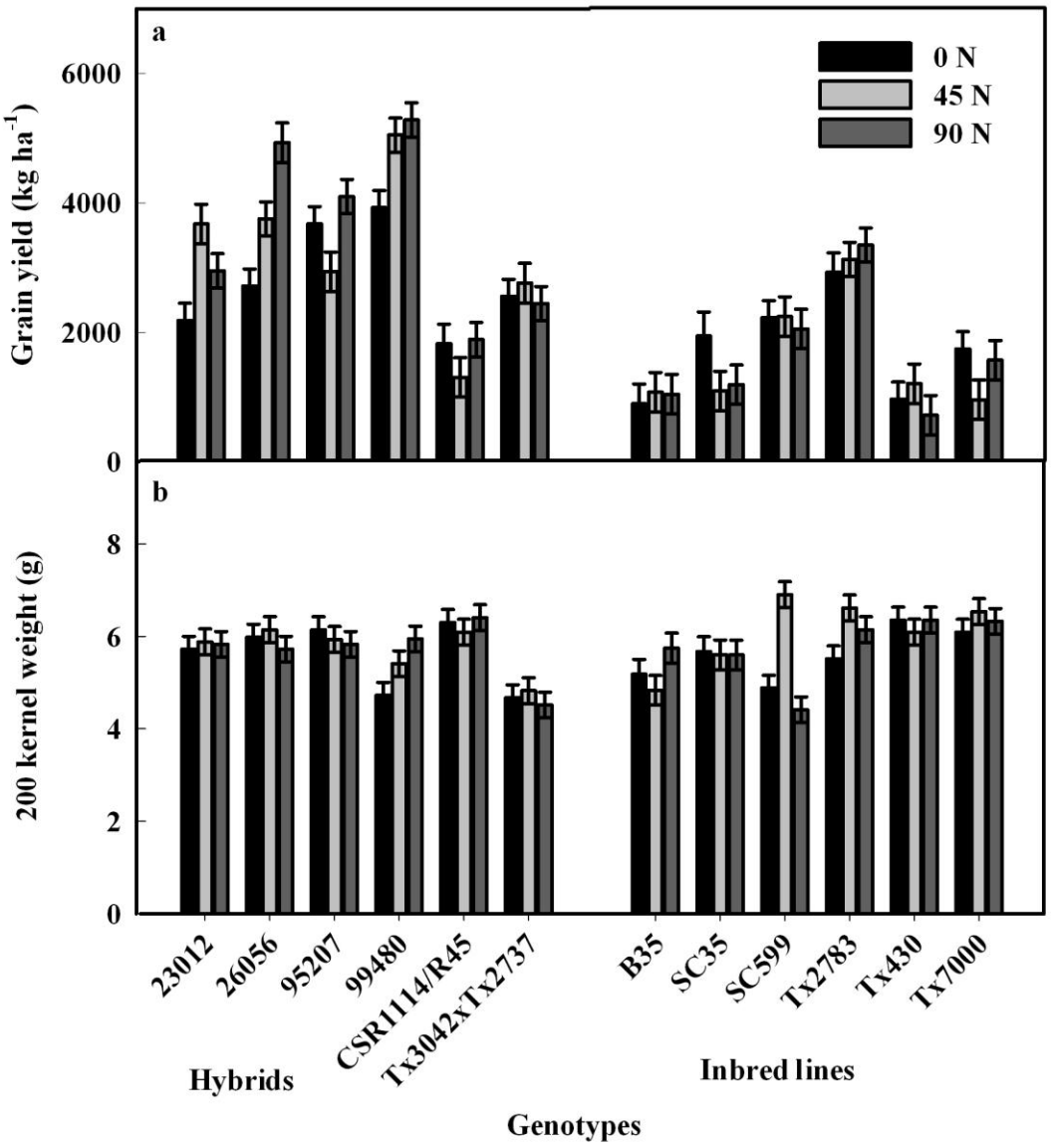

Figure 18. Genotype by nitrogen interaction on grain yield at Manhattan (Unit 7), Kansas, 2011.

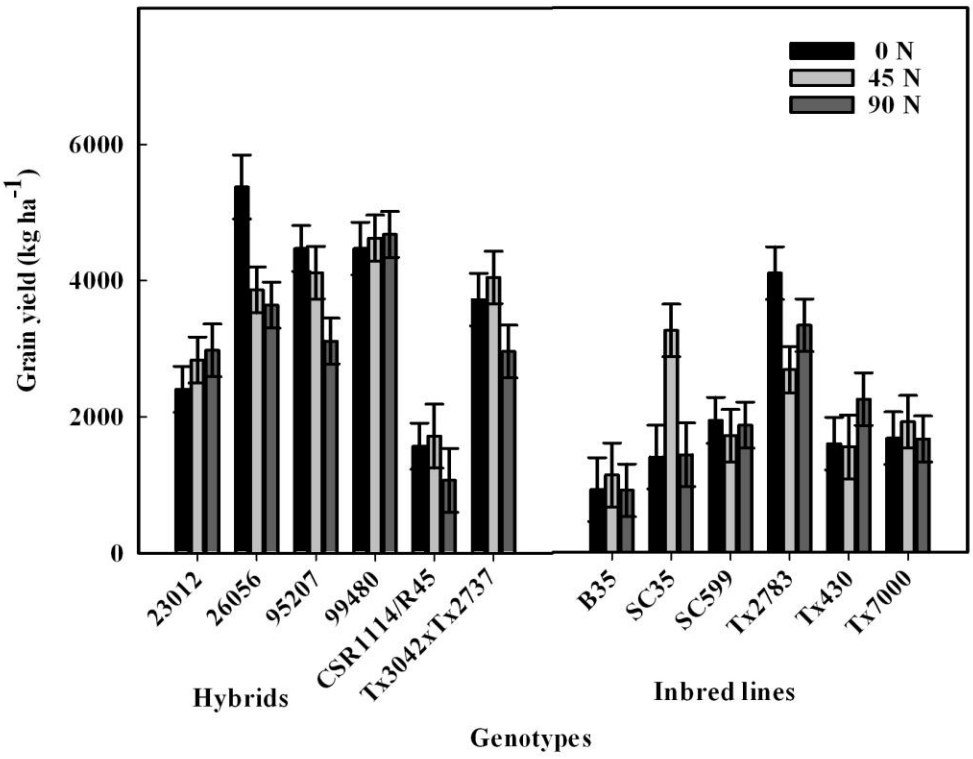

Figure 19. Genotype by nitrogen interaction effect on (a) leaves (b) stem and (c) total N at maturity at Manhattan (Unit 7), Kansas, 2010.

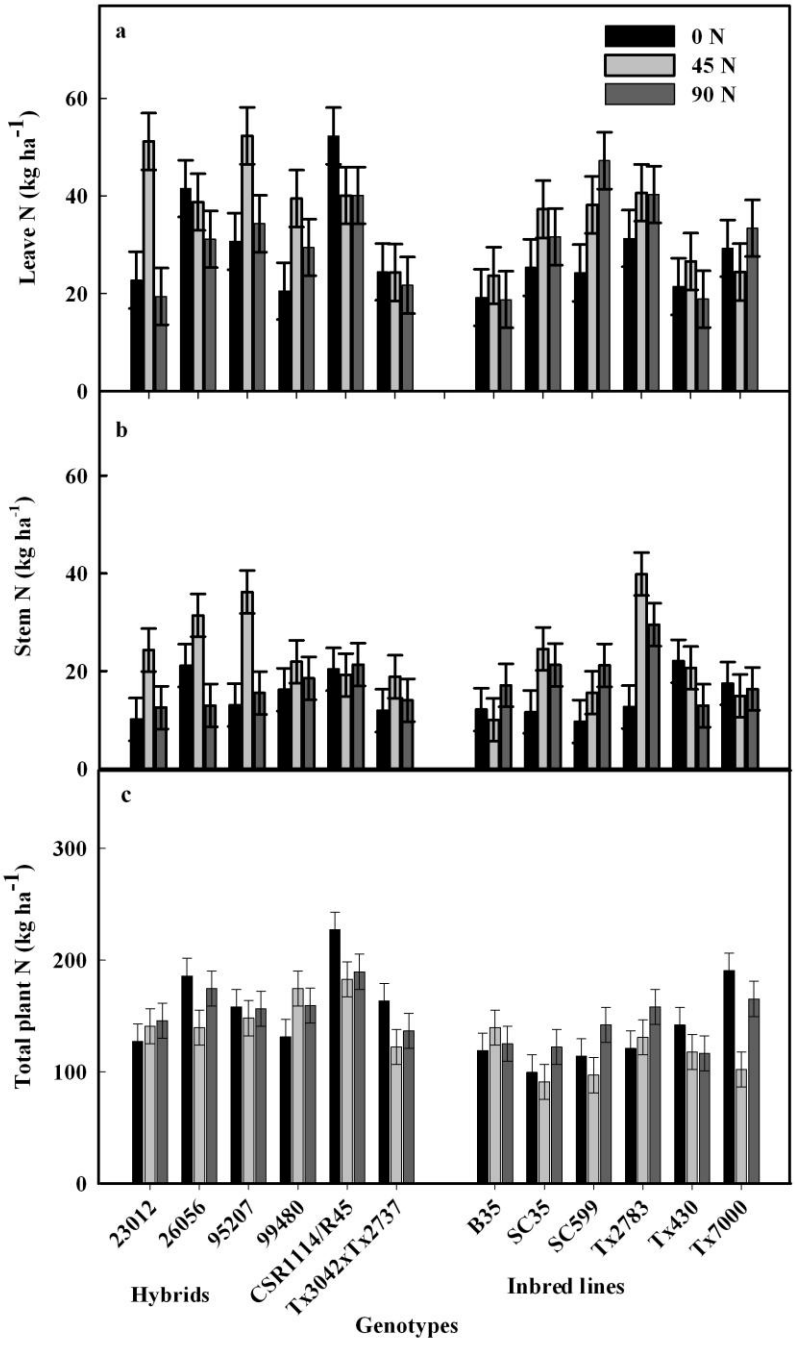

Figure 20. Genotype by nitrogen interaction effect on NUE and (b) N utilization efficiency of grain sorghum at Ottawa, Kansas, 2010.

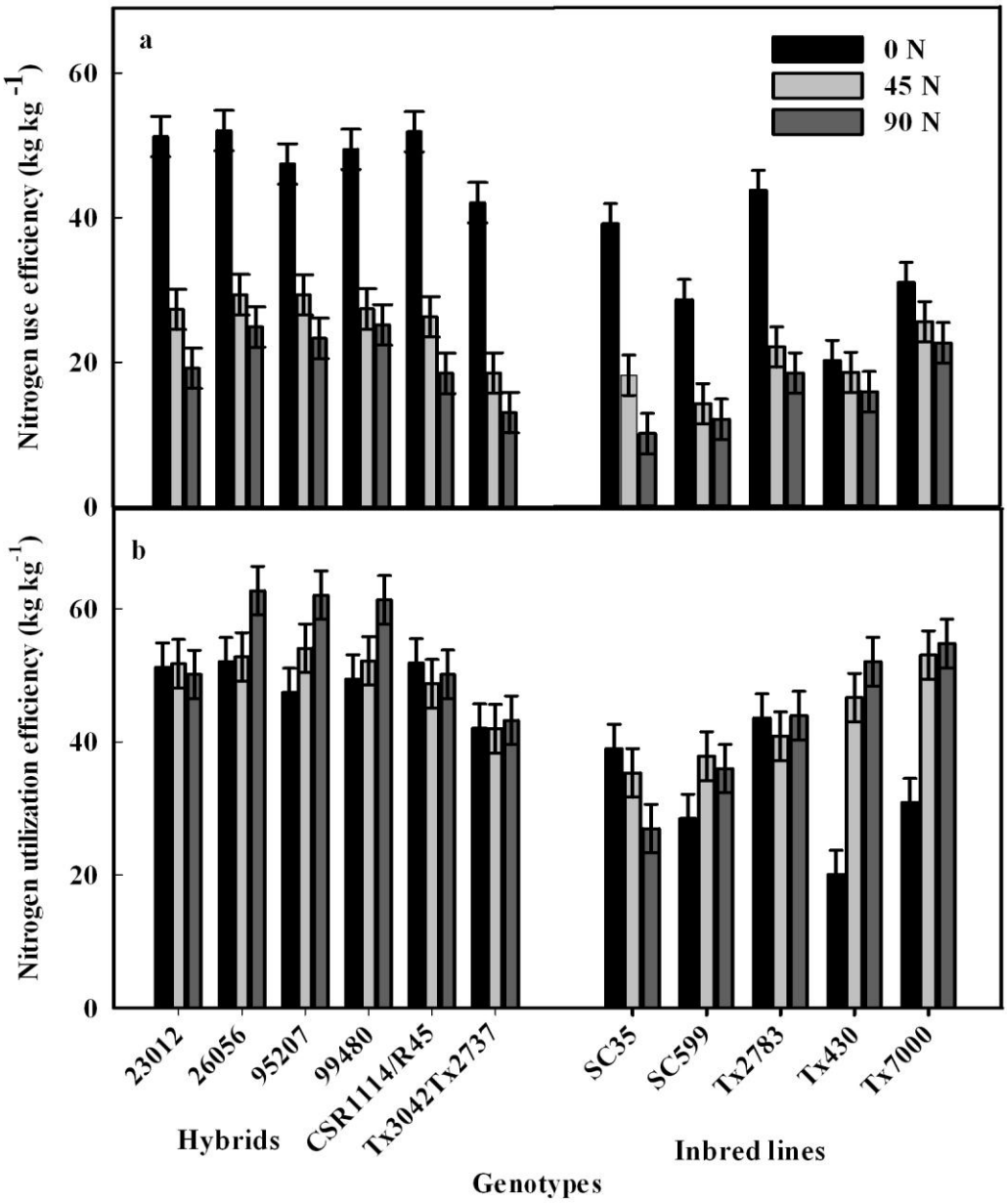

Figure 21. Genotype by nitrogen interaction effect on (a) nitrogen uptake efficiency and (b) nitrogen harvest index of grain sorghum at Ottawa, Kansas, 2010.

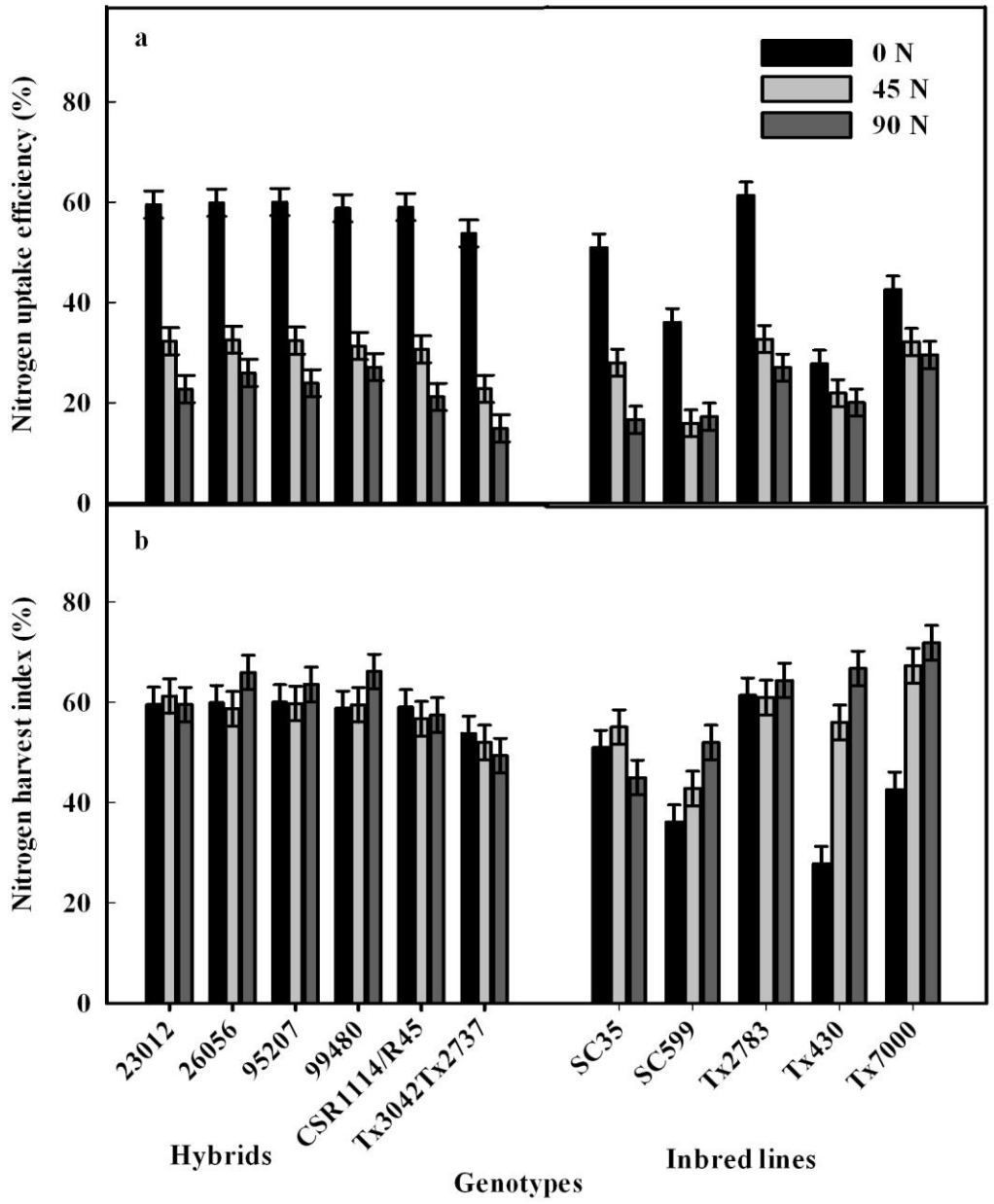

Figure 22. Genotype by nitrogen interaction effect on NUE at (a) Manhattan (Unit 7) and (b) Ottawa of grain sorghum at Ottawa, Kansas, 2011.

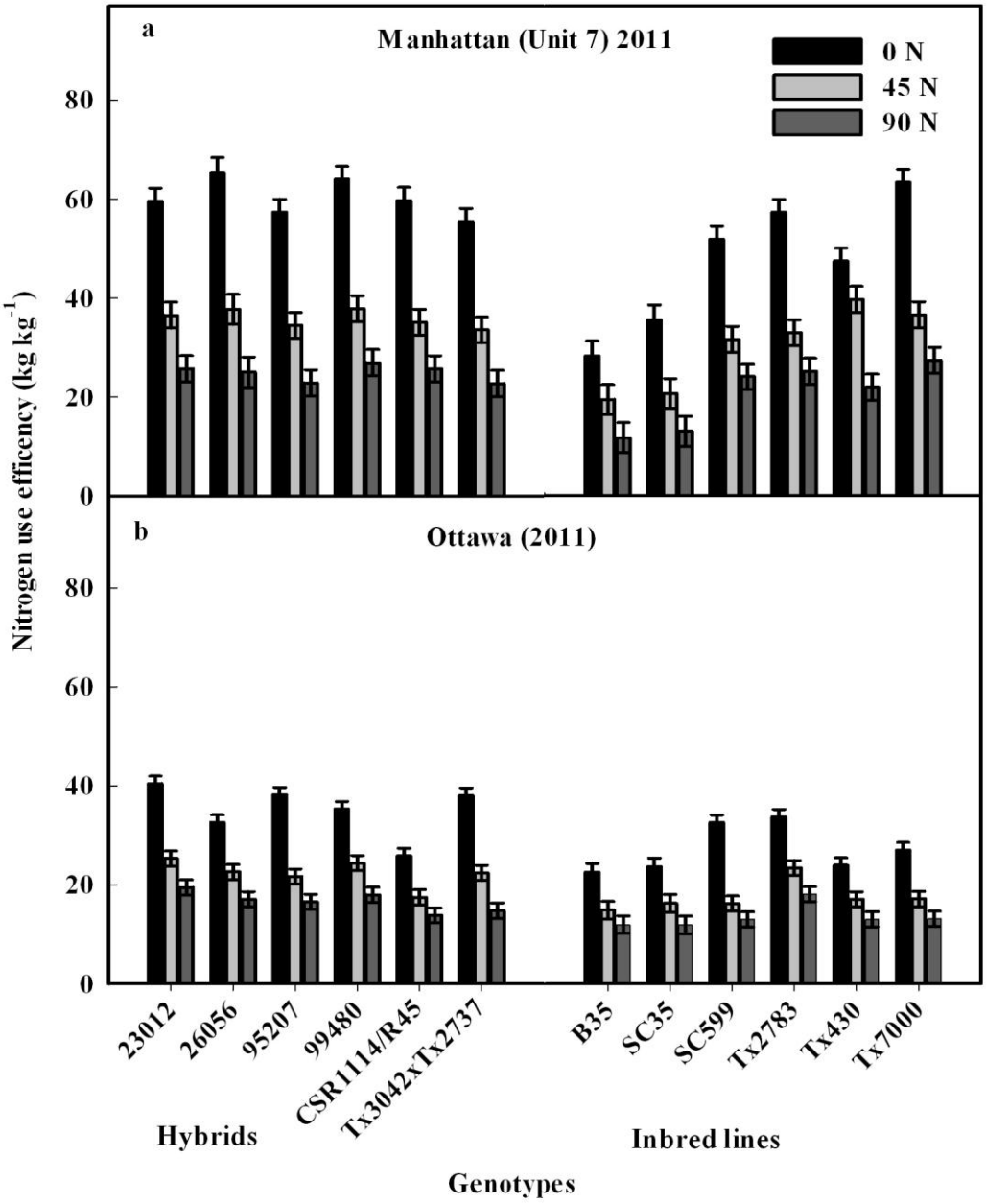

Figure 23. Genotype by nitrogen interaction effect on fertilizer nitrogen recovery nitrogen of grain sorghum at Ottawa, Kansas, 2011.

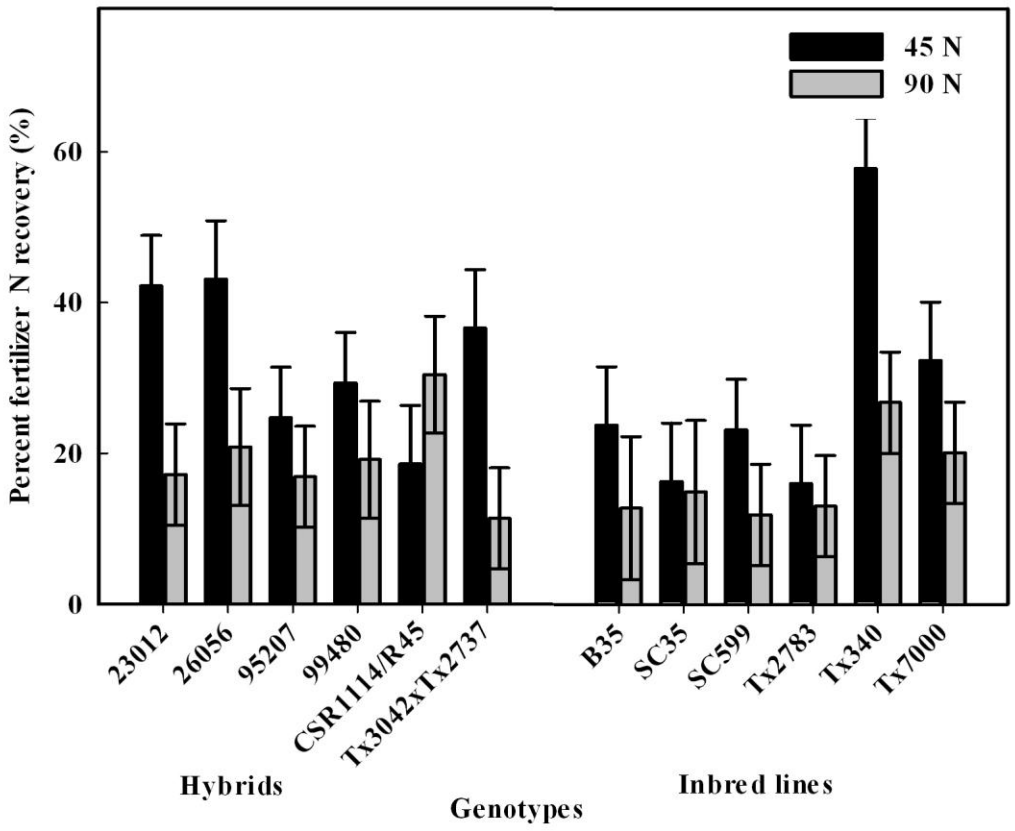

Figure 24. Change in total biomass at flowering of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 Kg N ha^{-1} in both years combined at Manhattan (unit1), Kansas. Numbers on bars indicates percentage change.

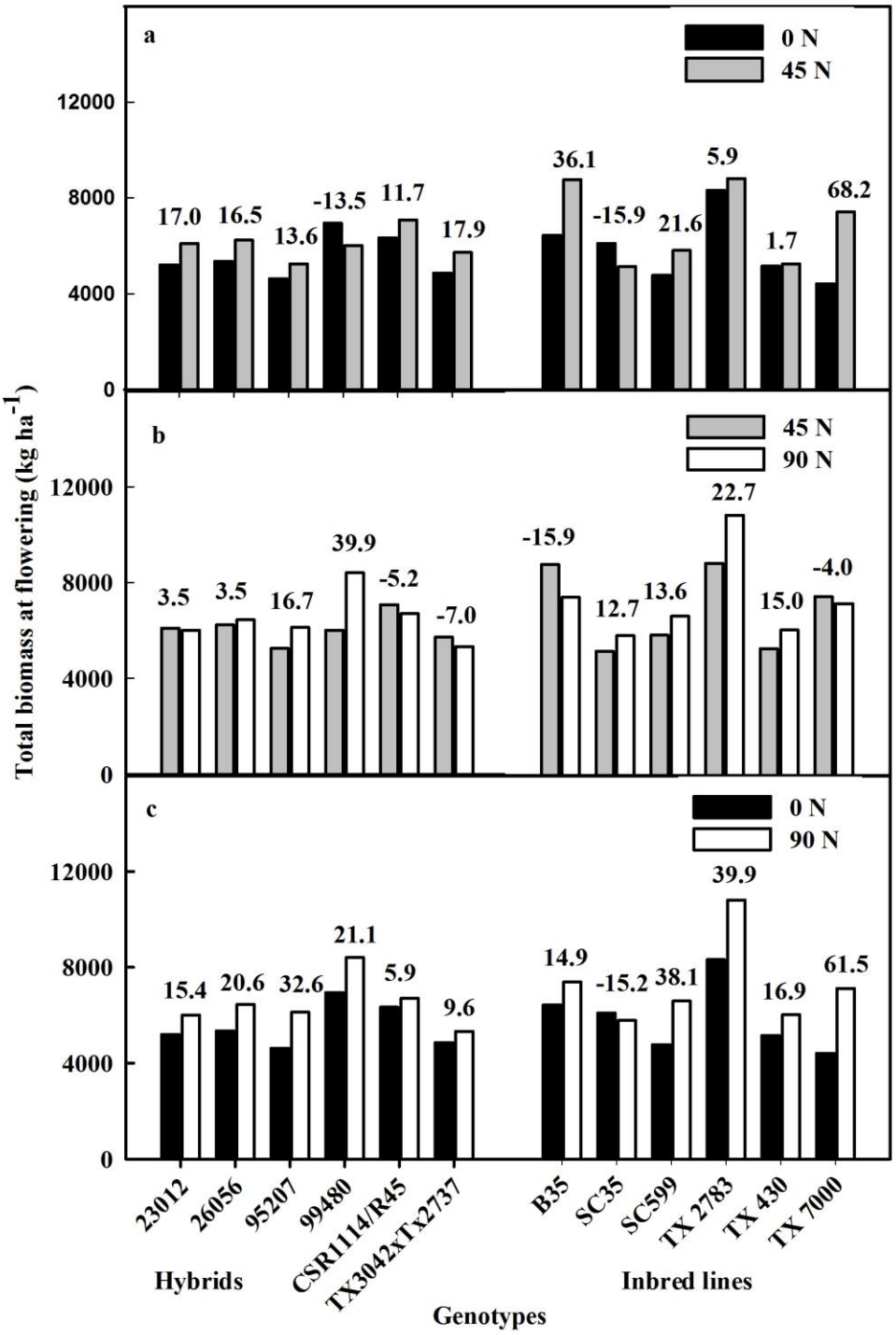

Figure 25. Change in total biomass at physiological maturity of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Manhattan (Unit 1), Kansas. Numbers on bars indicates percentage change.

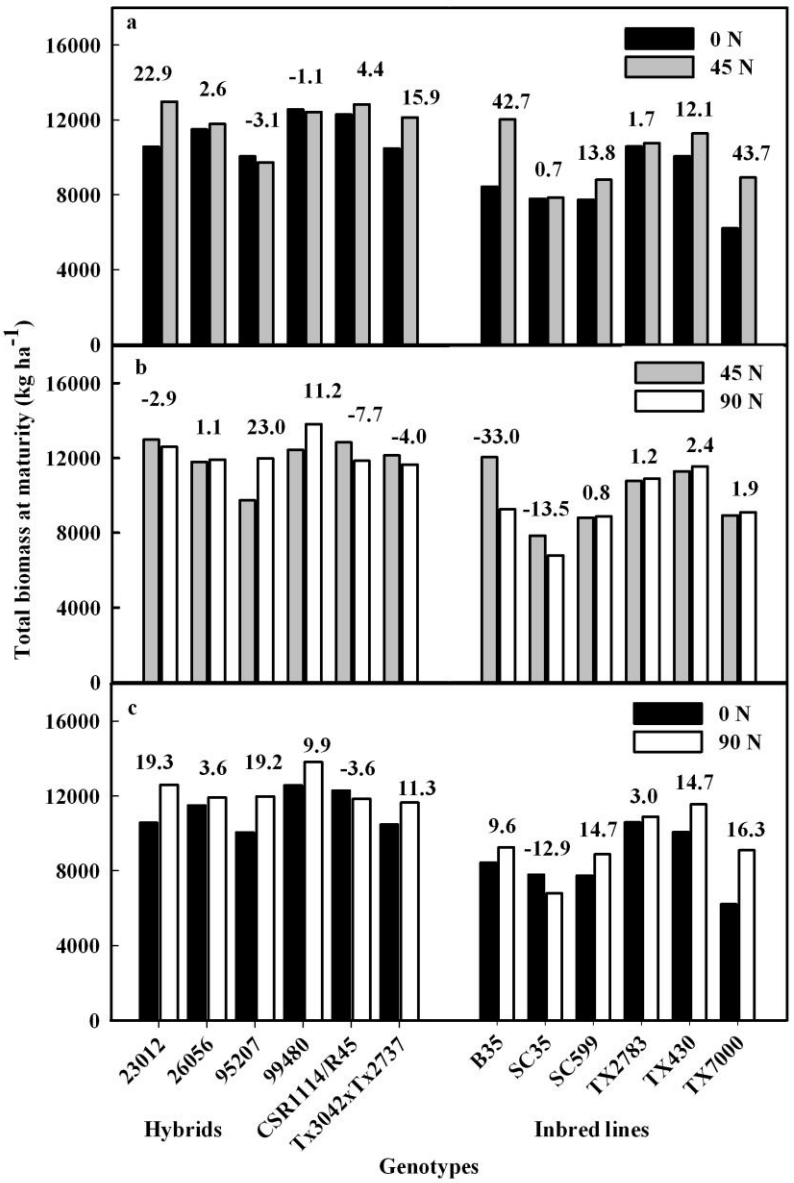

Figure 26. Change in grain yield of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Manhattan (Unit 1), Kansas. Numbers on bars indicates percentage changes.

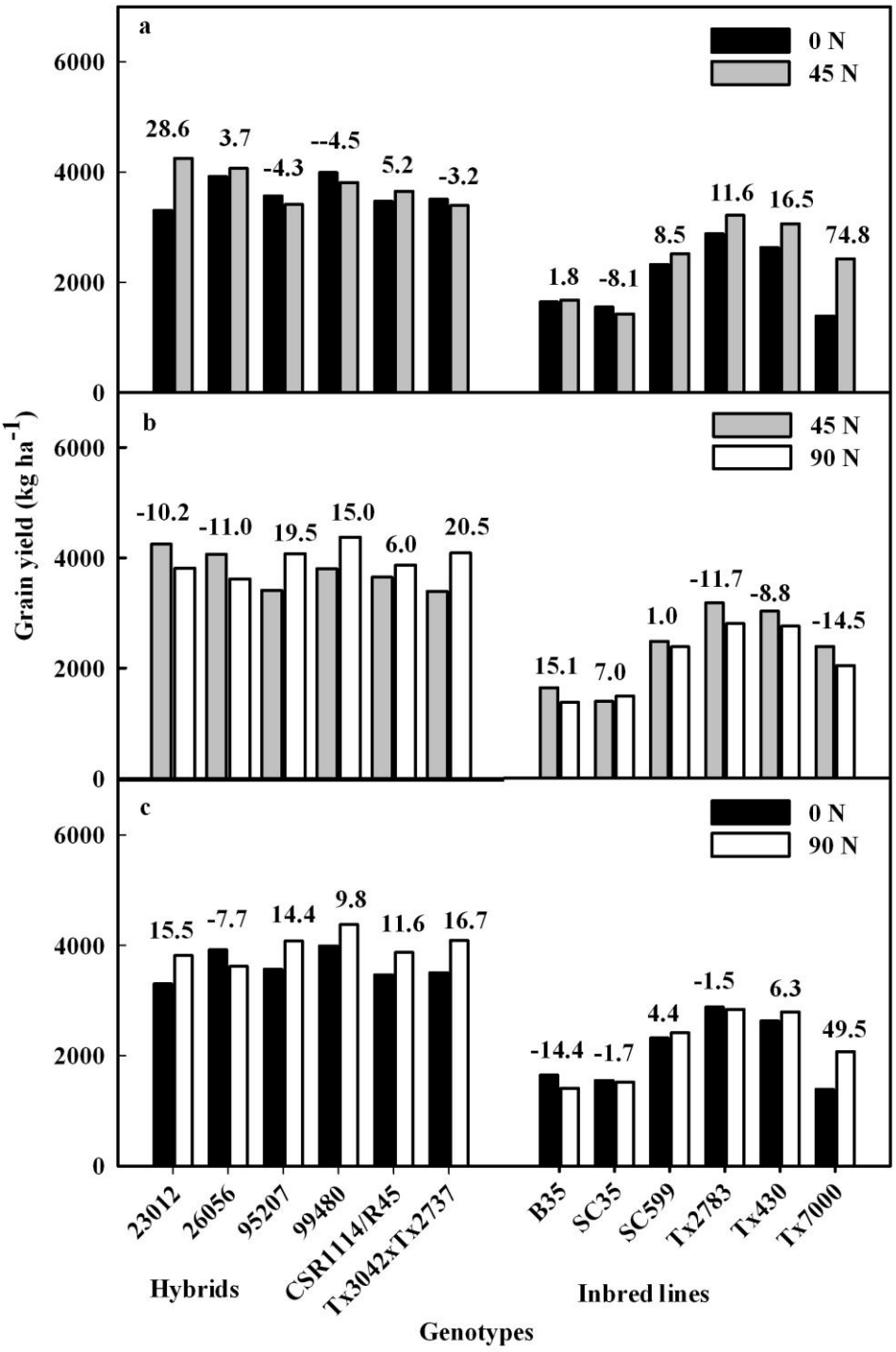

Figure 27. Change in total biomass at flowering of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Manhattan (Unit 7), Kansas. Numbers on bars indicates percentage change.

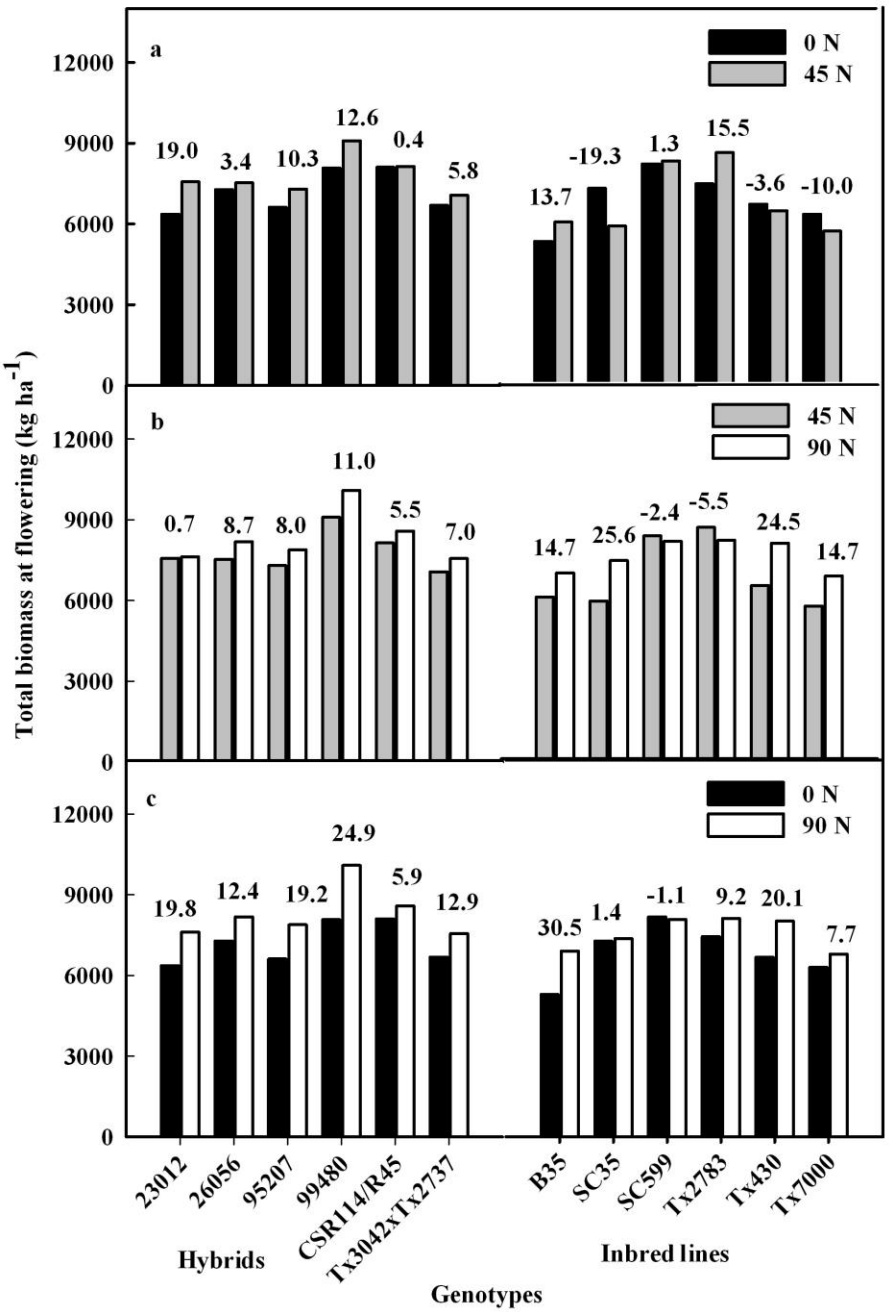

Figure 28. Change in total biomass at physiological maturity of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Manhattan (Unit 7), Kansas Numbers on bars indicates percentage change.

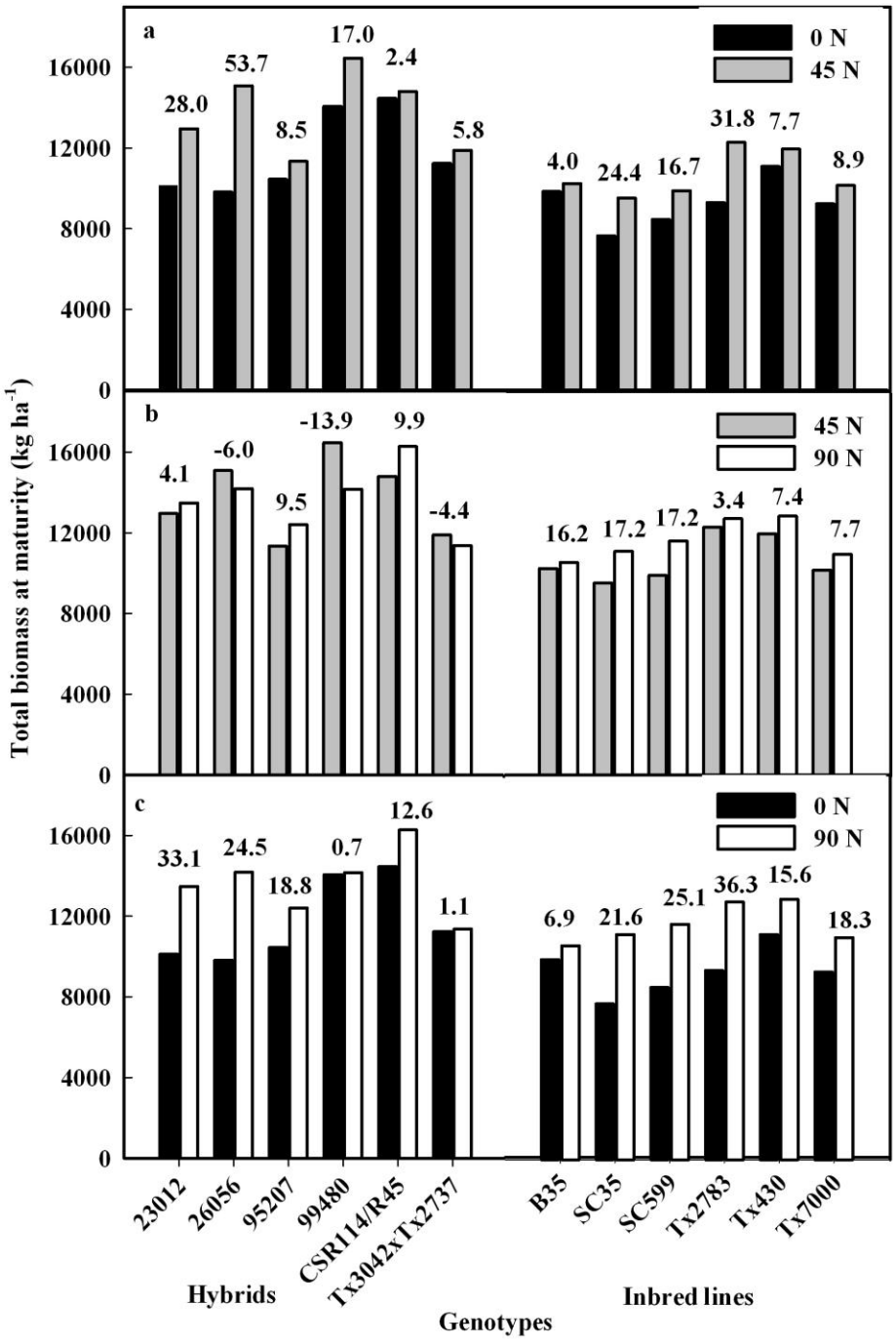

Figure 29. Change in grain yield of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Manhattan (Unit 7), Kansas. Numbers on bars indicates percentage change.

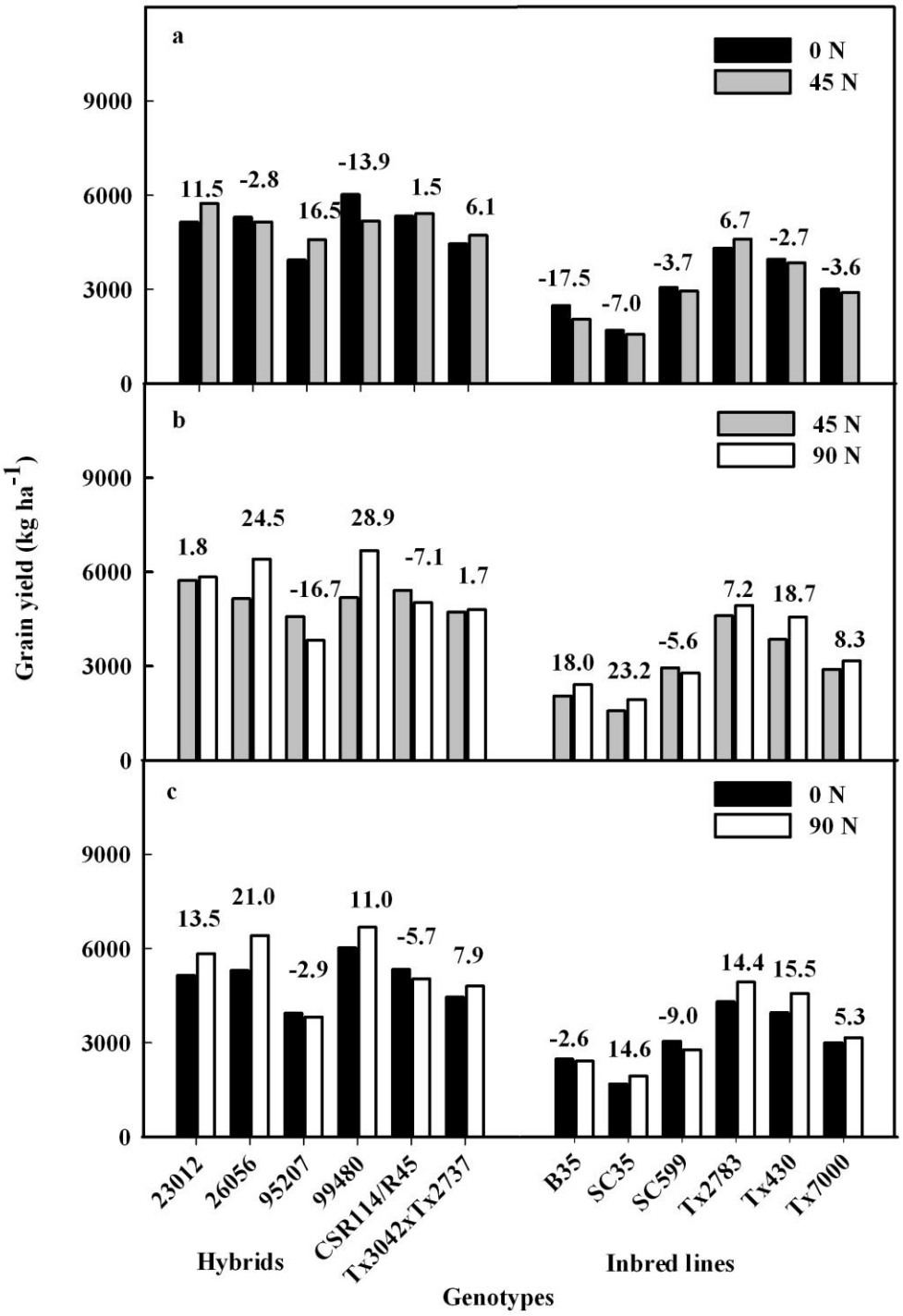

Figure 30. Change in total biomass at flowering of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Ottawa, Kansas. Numbers on bars indicates percentage change.

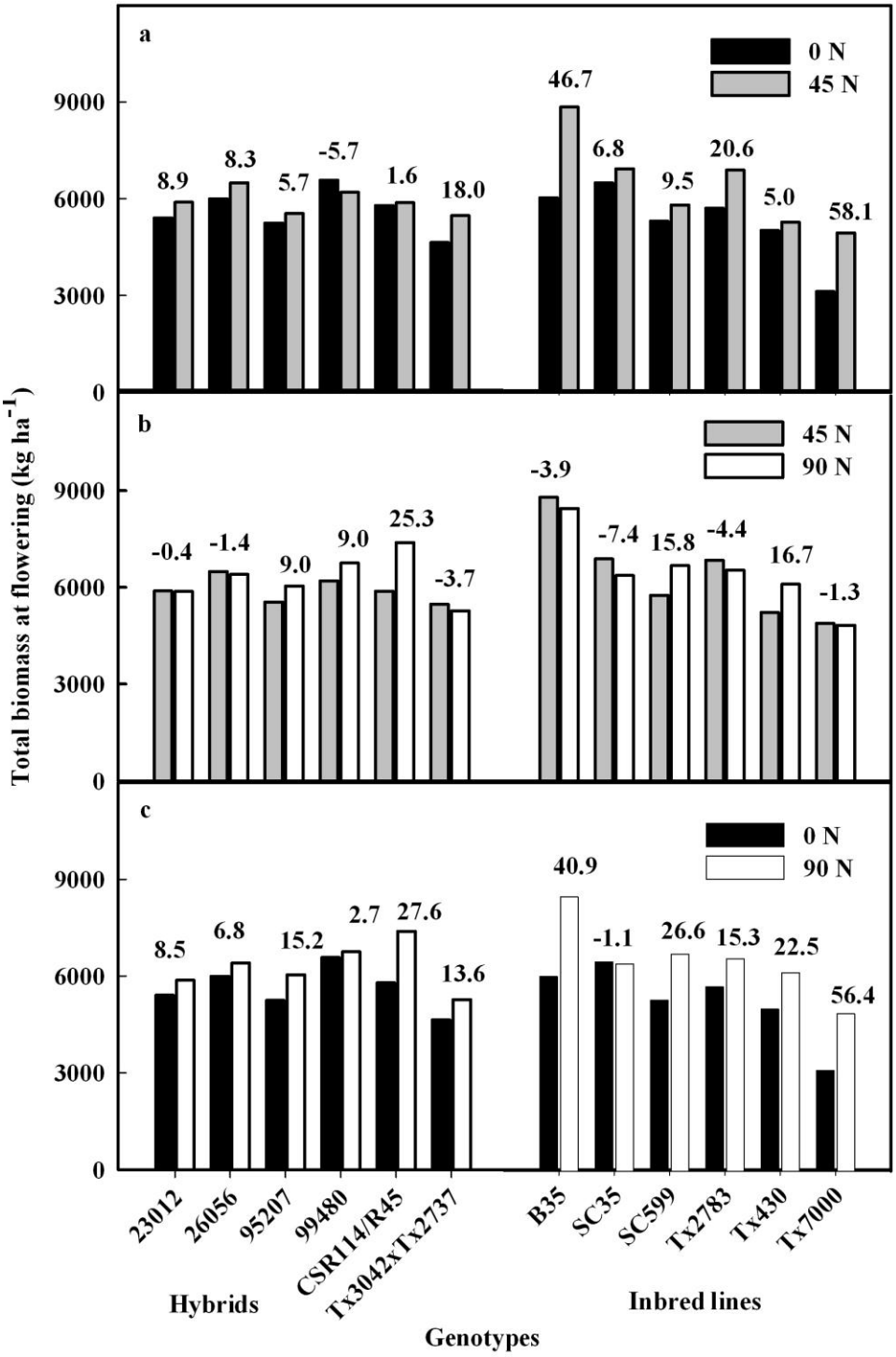

Figure 31. Change in total biomass at physiological maturity of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Ottawa, Kansas. Numbers on bars indicates percentage change.

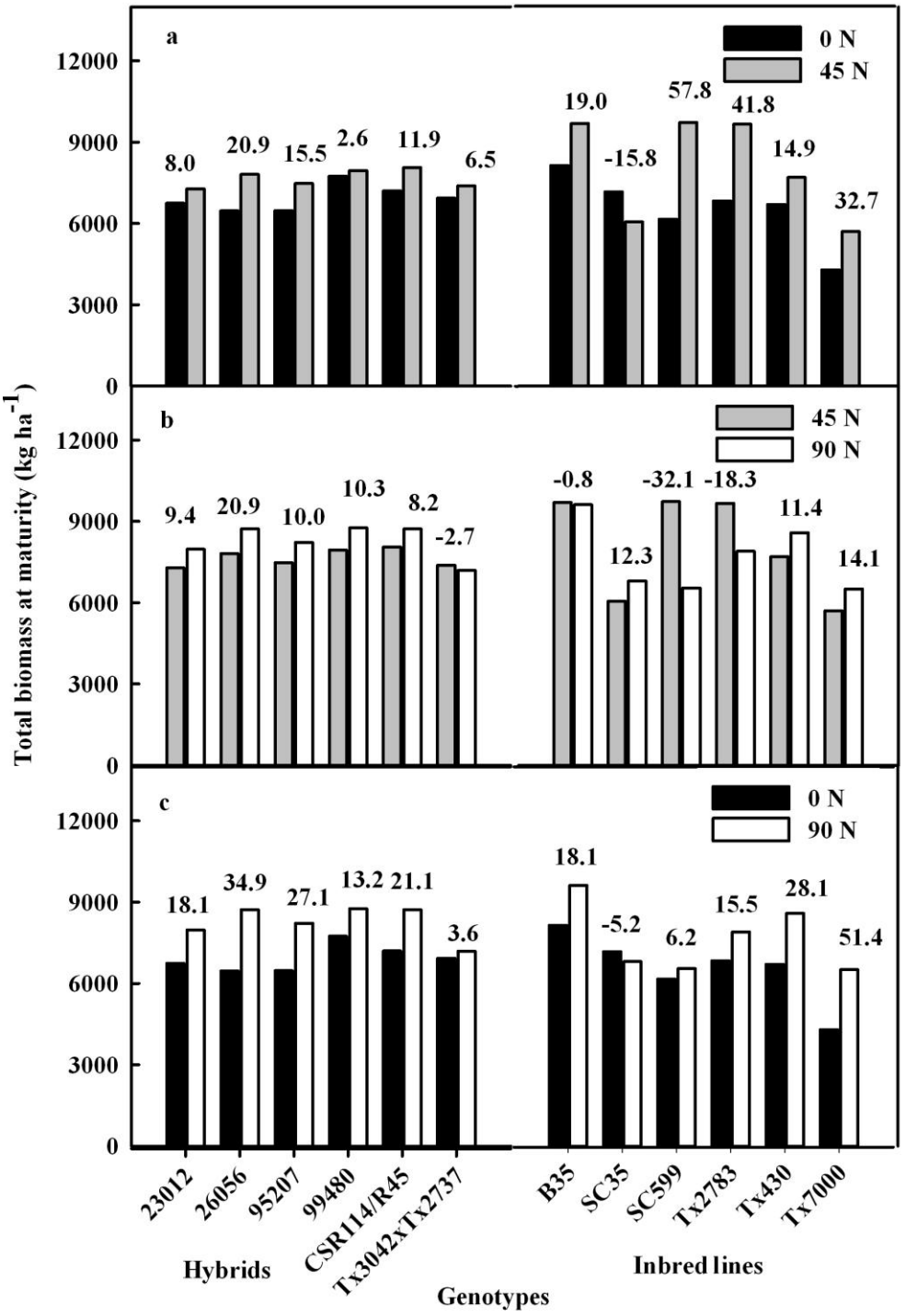

Figure 32. Change in grain yield of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Ottawa, Kansas. Numbers on bars indicates percentage change.

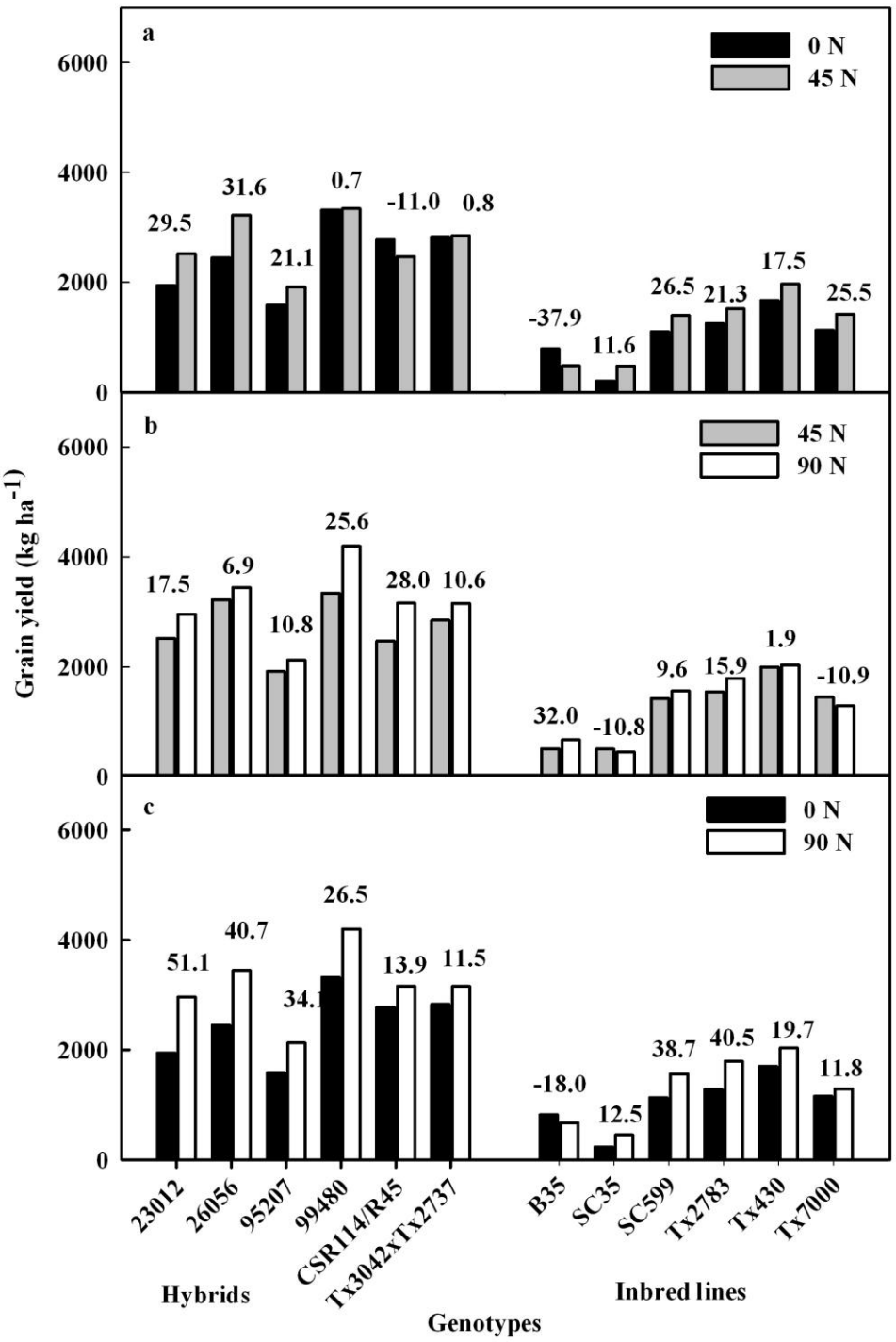

Figure 33. Change in total biomass at flowering of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 kg N ha^{-1} in both years combined at Hays, Kansas. Numbers on bars indicates percentage change.

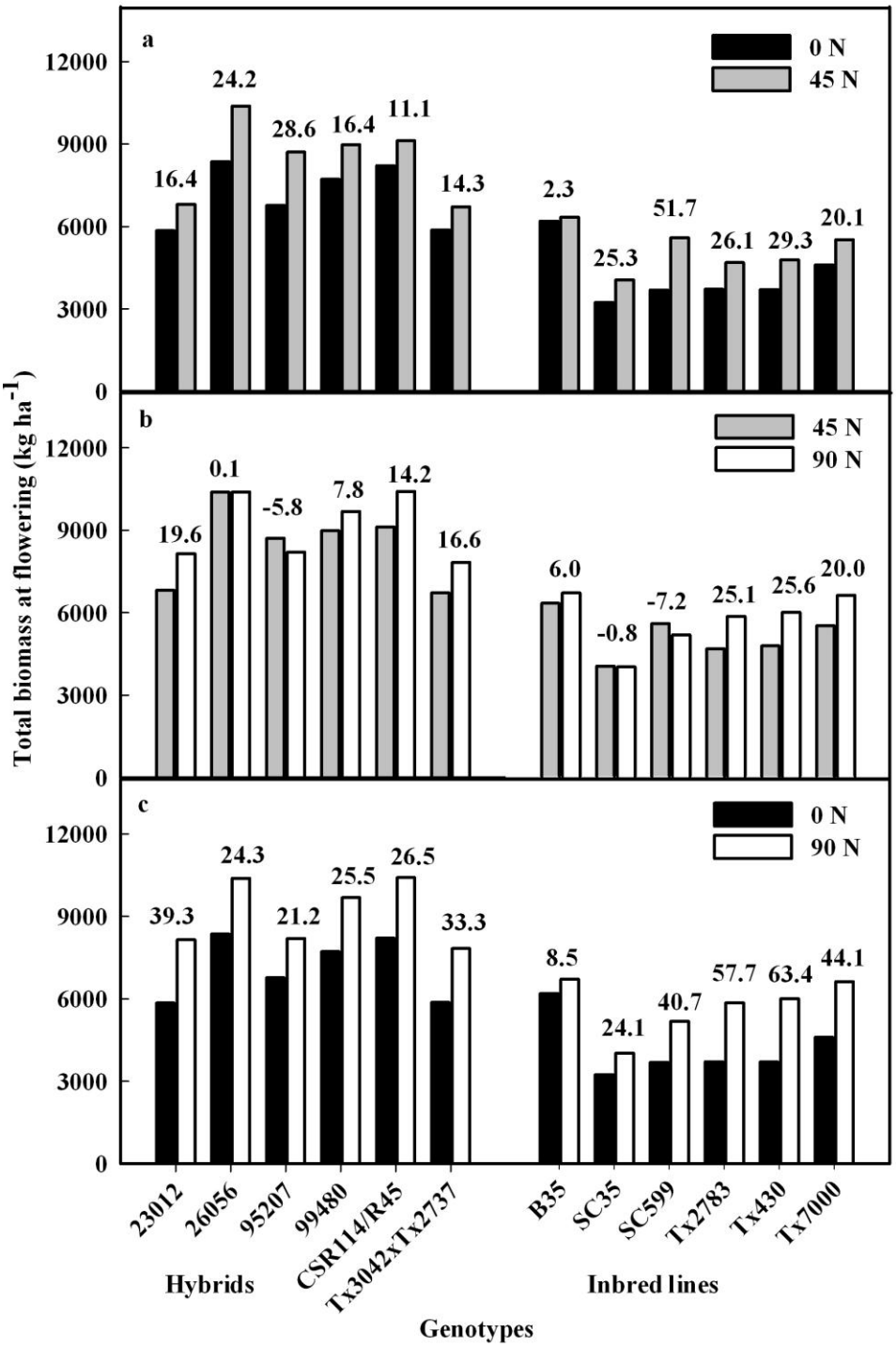

Figure 34. Change in total biomass at physiological maturity of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 Kg N ha^{-1} in both years combined at Hays, Kansas. Numbers on bars indicates percentage change.

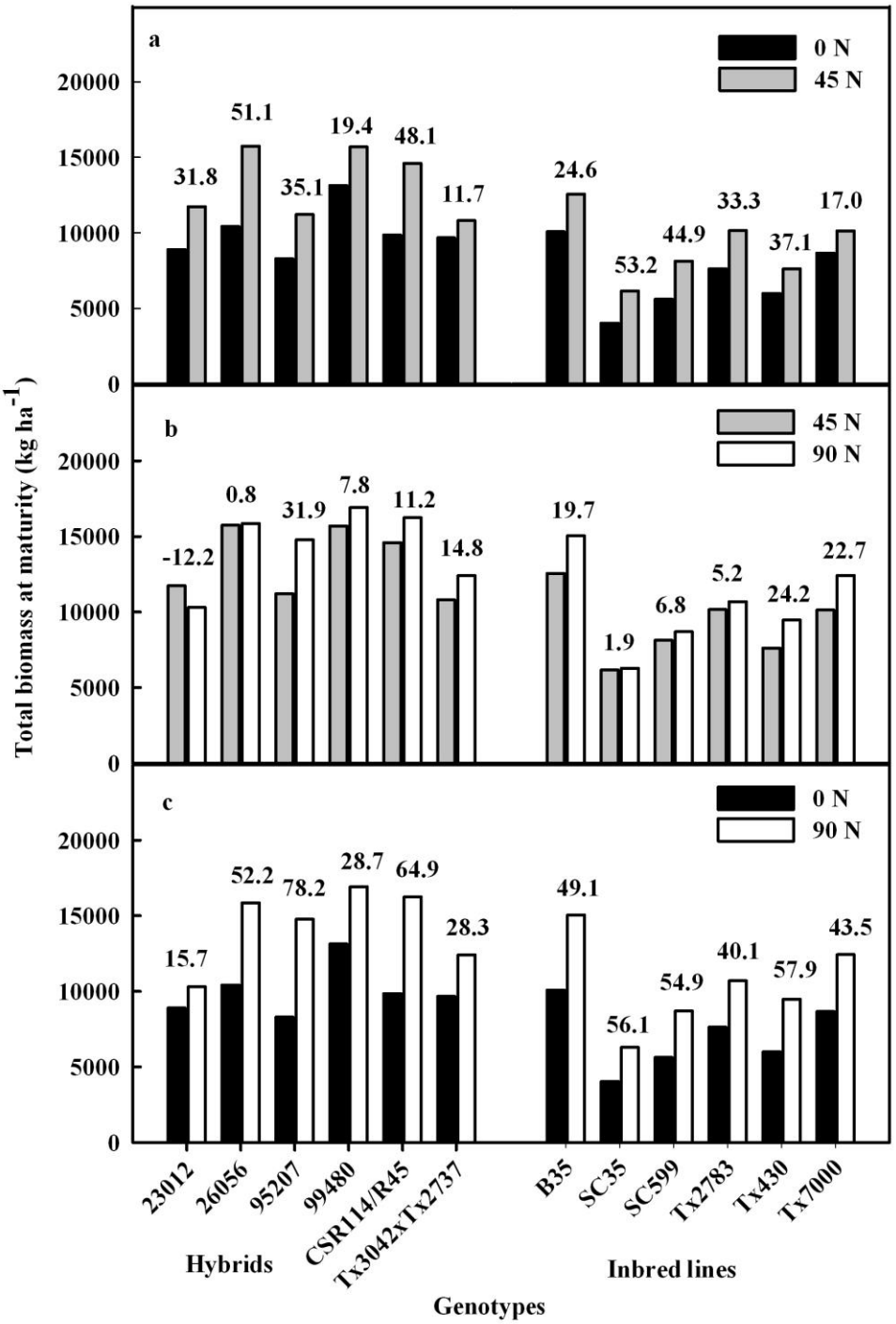

Figure 35. Change in grain yield of different genotypes due to nitrogen application (a) changes from 0 kg N ha^{-1} to 45 kg N ha^{-1} (b) 45 kg N ha^{-1} to 90 kg N ha^{-1} and (c) 0 kg N ha^{-1} to 90 Kg N ha^{-1} in both years combined at Hays, Kansas. Numbers on bars indicates percentage change.

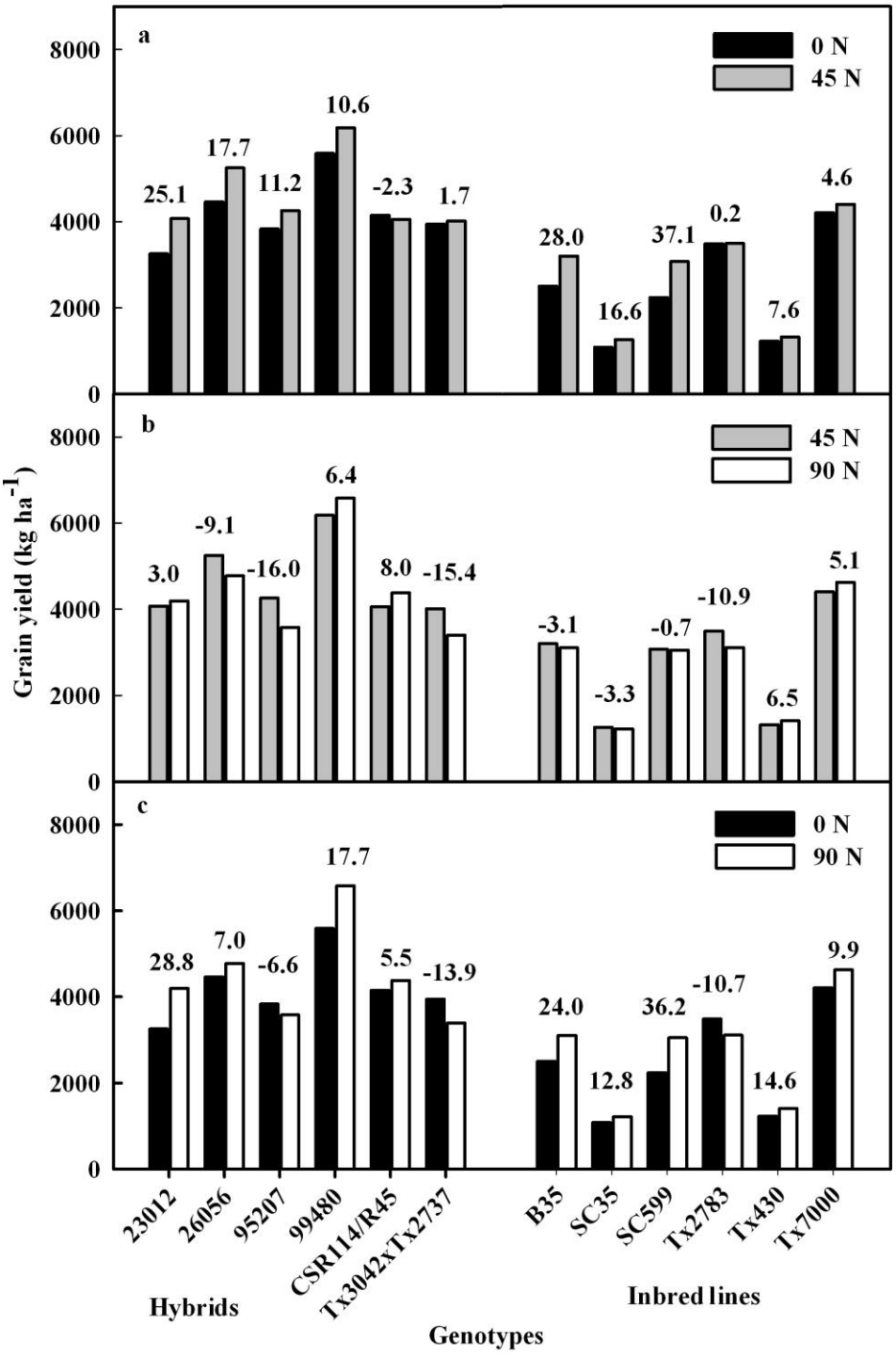

Figure 36**.** Photochemical efficiency (Fv/Fm) as function of leaf chlorophyll content at (a) vegetative (b) flowering and (c) physiological maturity at all locations and years combined.

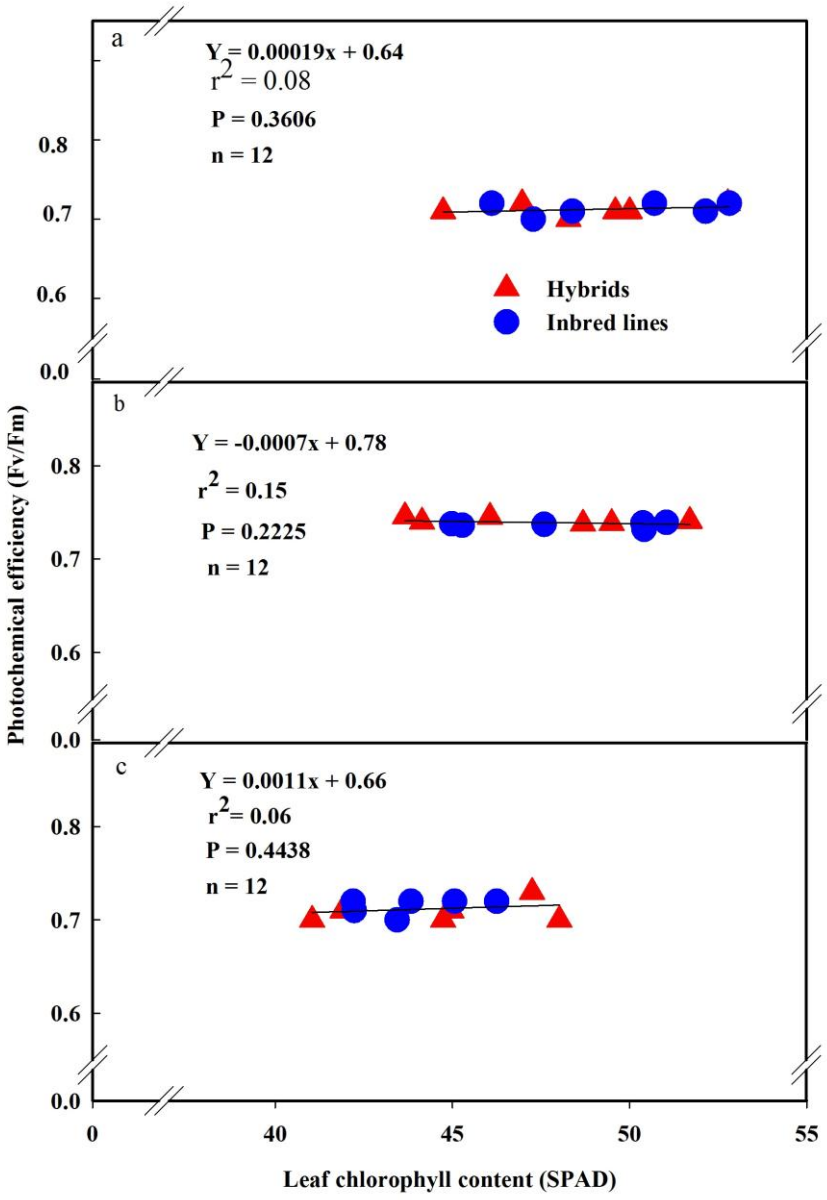

Figure 37. Leaf chlorophyll content (SPAD) as a function of grain yield at all locations and years combined.

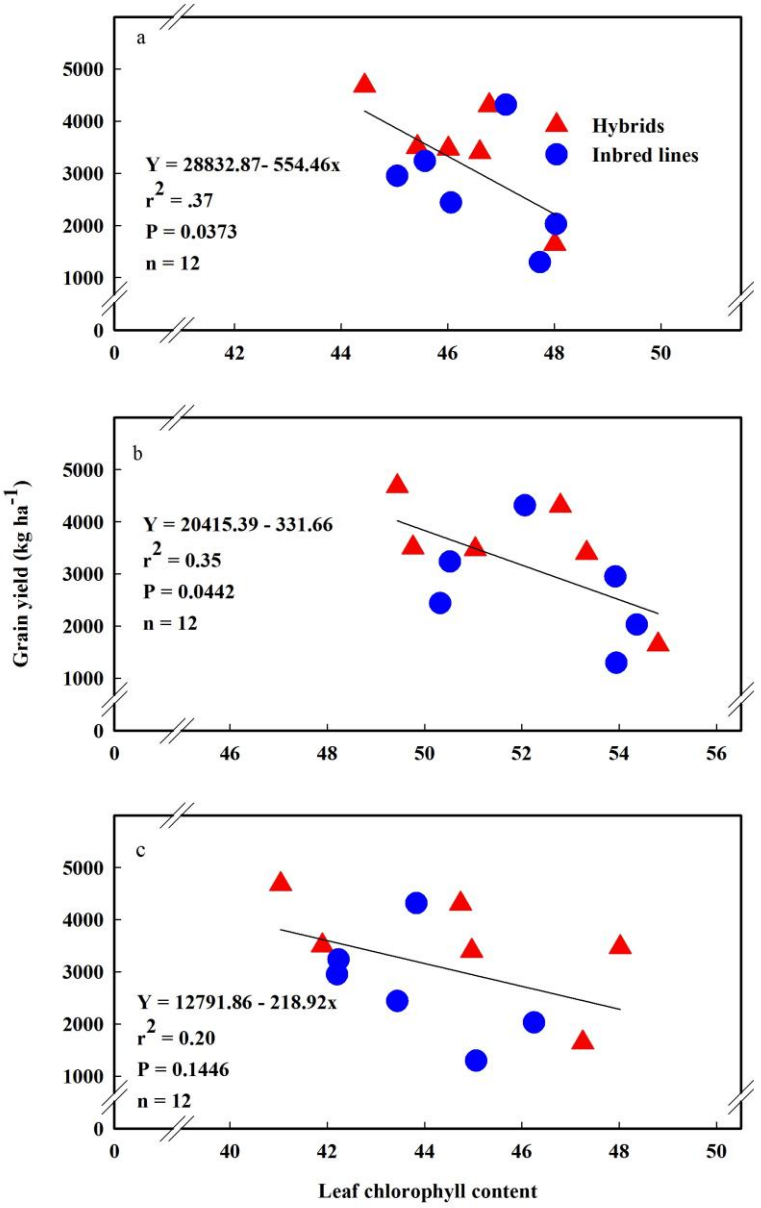

Figure 38. Photochemical efficiency (Fv/Fm) as a function of grain yield at all locations and years combined.

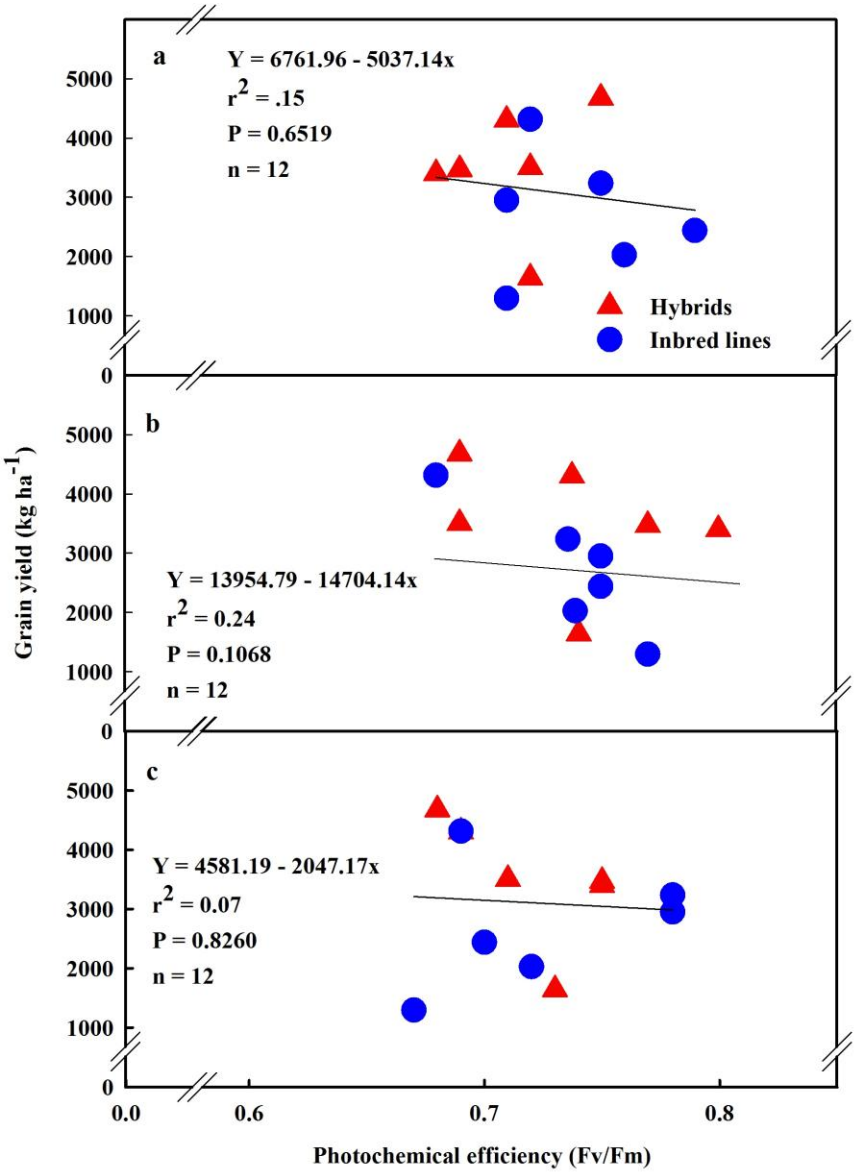

Figure 39. Grain yield as a function of total biomass at (a) vegetative (b) flowering and (c) physiological maturity at all locations and years combined.

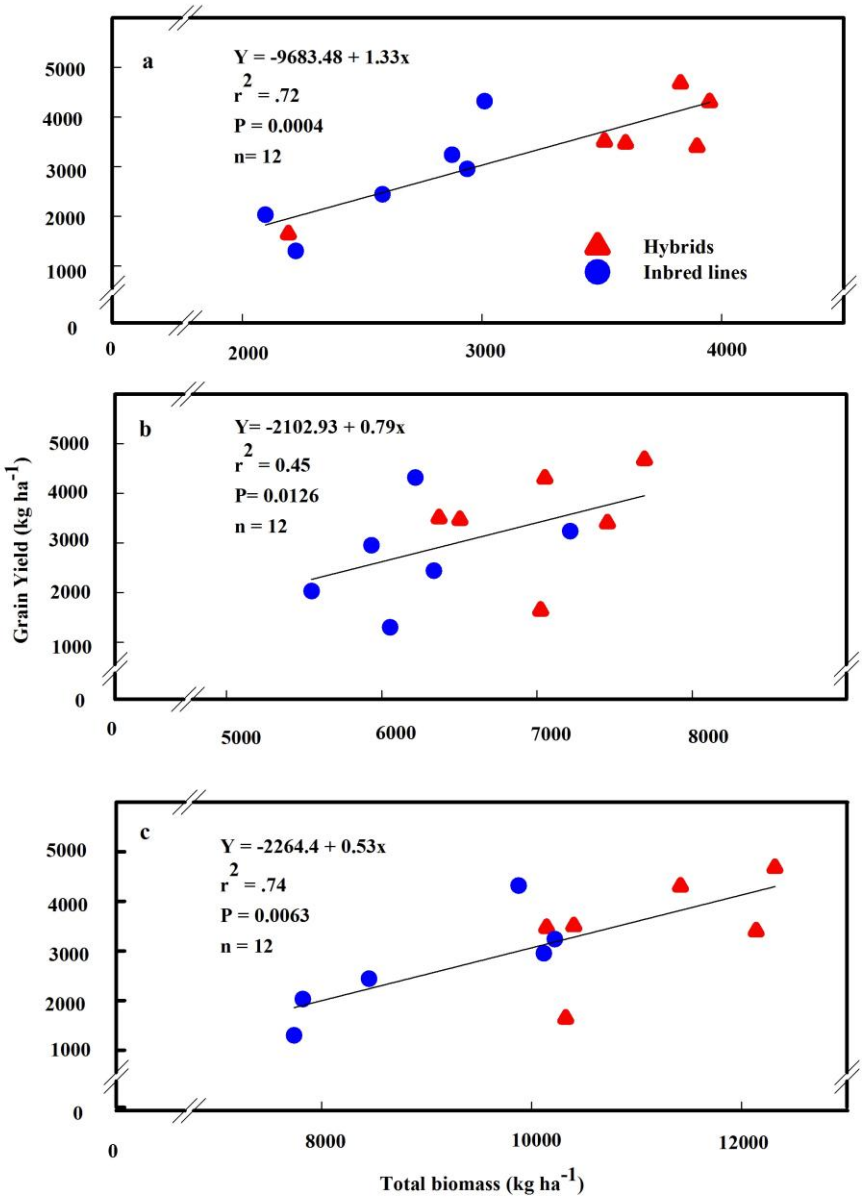

Figure 40. Grain yield as a function of (a) harvest index (b) 200 kernel weight (g) and (c) number of kernels (m^{-2}) at all locations and years combined.

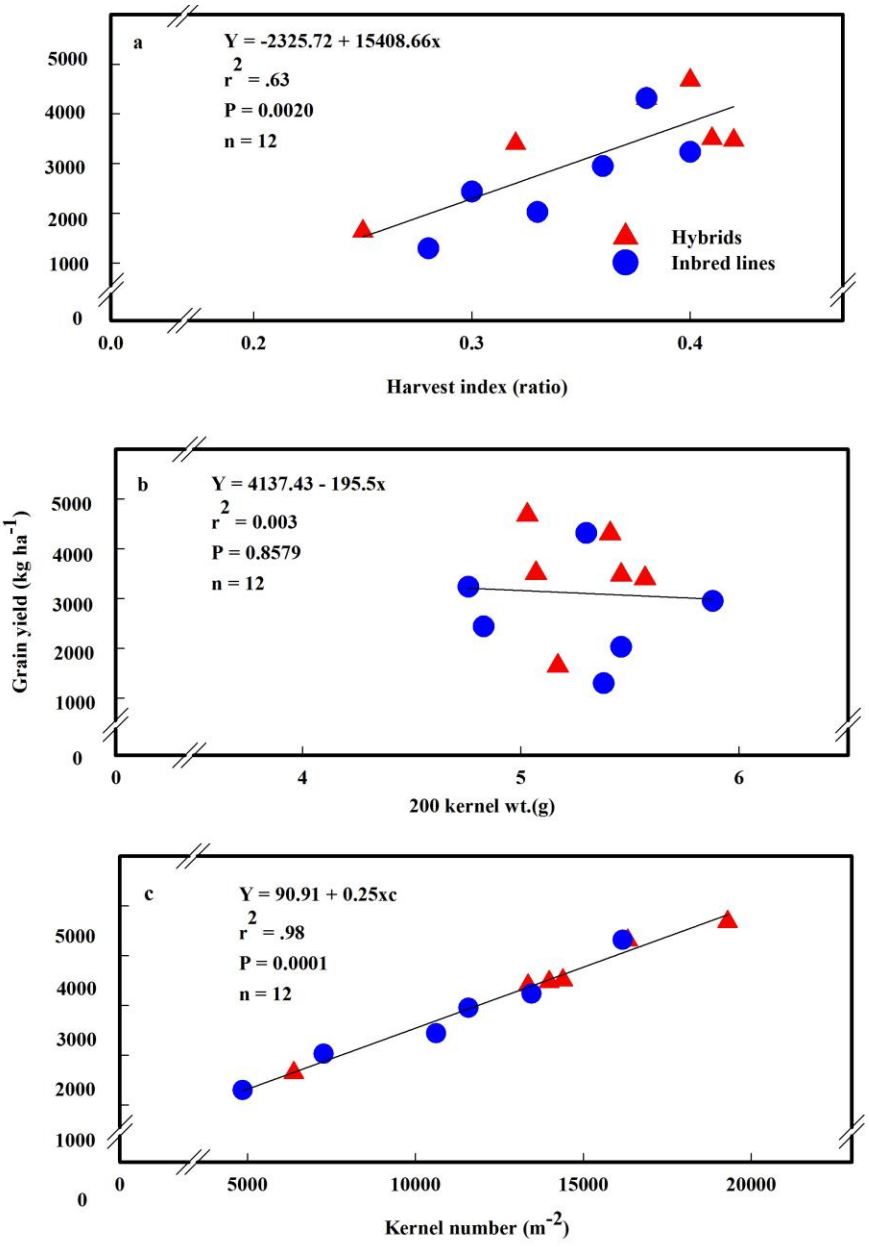

Figure 41. Grain N as a function of (a) grain yield (b) total biomass and (c) total plant N at Manhattan (Unit 7), Kansas, 2010 and 2011.

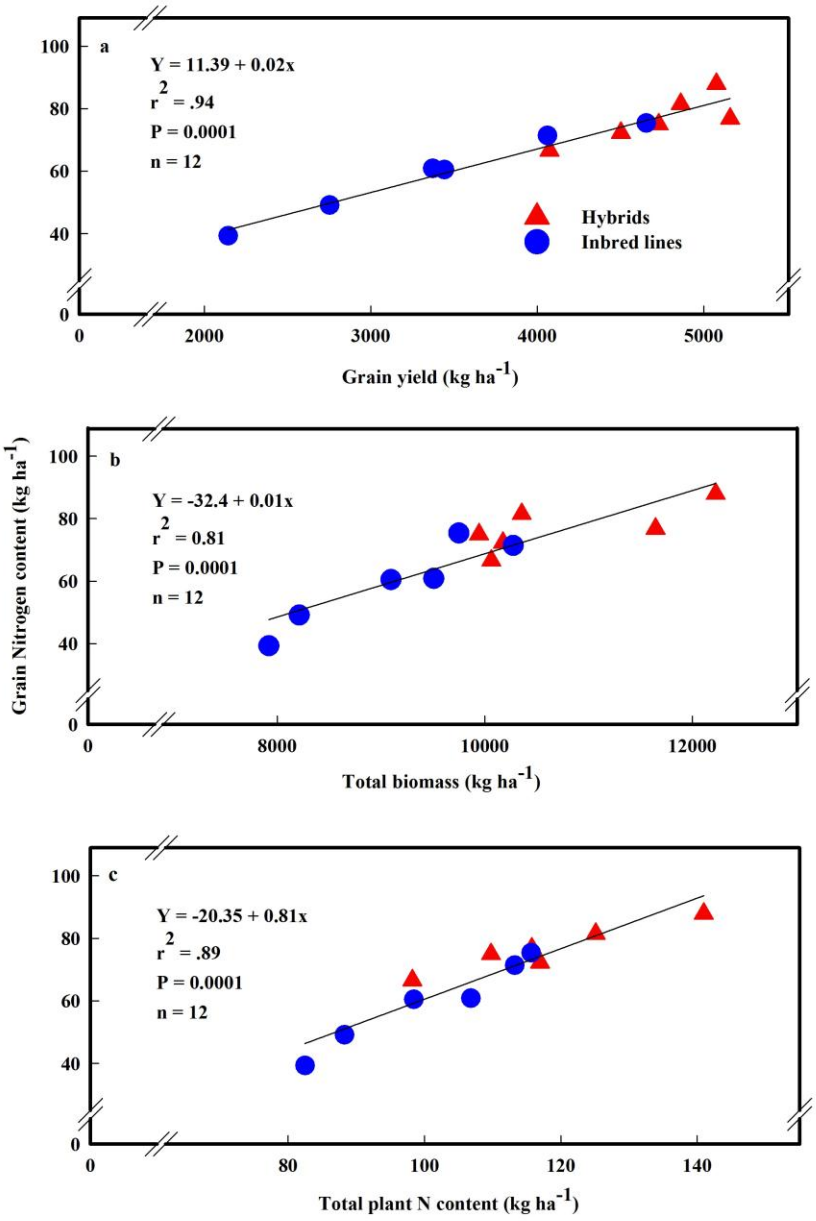

Figure 42. Grain N as a function of (a) grain yield (b) total biomass and (c) total plant N at Ottawa, Kansas, 2010 and 2011.

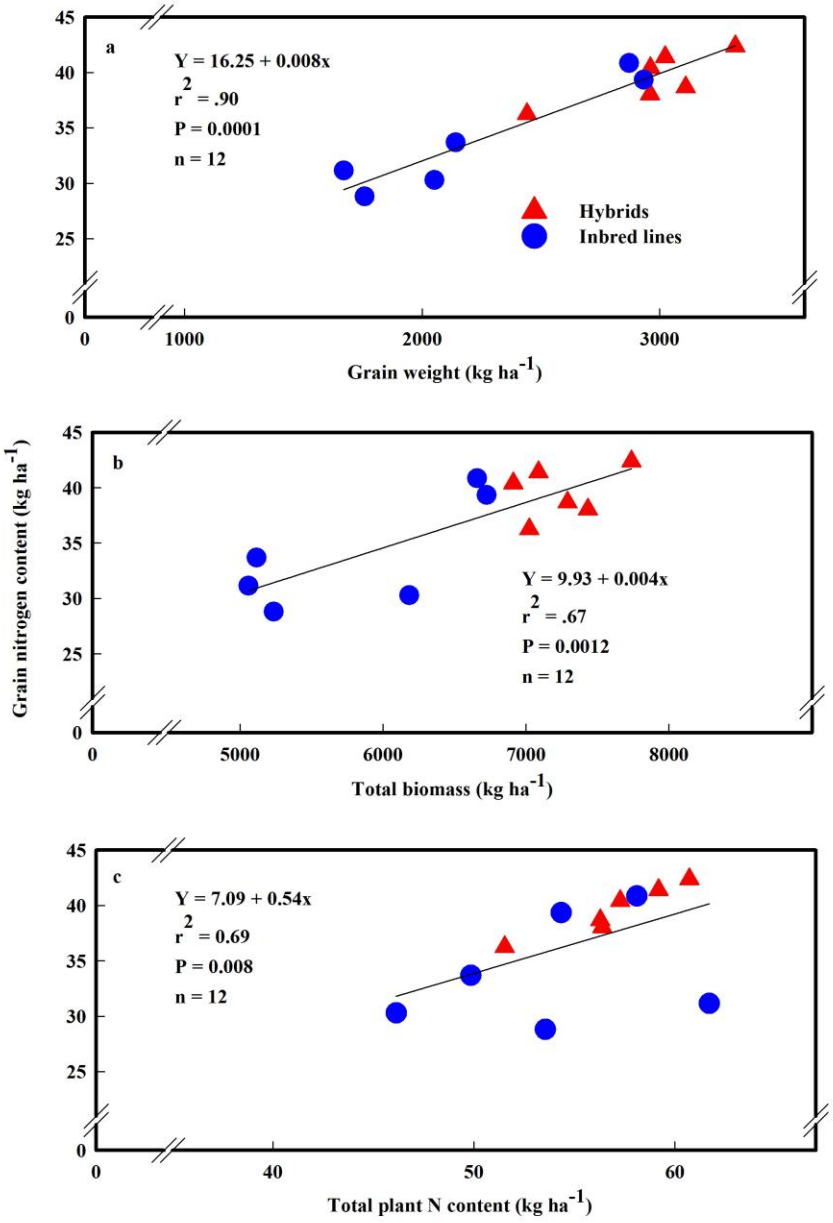

Table 1. Chemical and physical characteristics of soils from study area in 2010 and 2011.

Location	pH	Mehlich P	K	Sand	Silt	Clay	OM	Cl^-	SO_4-S	NH_4-N	NO_3-N
		mg kg^{-1}	mg kg^{-1}	%	%	%	%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
…… 2010 ……											
Manhattan (Unit 1)	6.2	42.1	270.3	23.5	63.5	13.0	1.2	10.0	4.2	1.9	6.0
Manhattan (Unit 7)	6.4	52.3	387.3	4.5	68.5	27.0	2.6	6.2	5.8	3.0	13.8
Ottawa	6.2	11.2	122.3	8.7	64.0	27.3	2.8	14.4	5.0	3.7	2.2
Hays	6.0	61.4	663.5	12.0	61.0	27.0	1.8	3.4	3.9	2.3	7.6
…… 2011 ……											
Manhattan (Unit 1)	6.1	34.0	227.0	17.0	73.0	10.0	1.6	2.9	2.7	4.1	5.2
Manhattan (Unit 7)	7.5	56.1	293.5	6.0	75.0	19.0	1.5	4.3	3.4	4.1	7.7
Ottawa	6.0	14.9	117.5	2.0	72.0	26.0	1.8	5.7	7.2	7.1	16.6

OM = organic matter Cl^- = chlorine

Table 2. Key characteristics and source of genotypes used in the experiment during 2010 and 2011 seasons.

Genotypes	Type	Characteristics	Source
23012	Hybrid	PreDFR, PostFDR	Crosbyton
26056	Hybrid	PreFDS, PostFDR	Crosbyton
95207	Hybrid	PreFDR, PostFDS	Crosbyton
99480	Hybrid	PreFDS, PostFDR	Crosbyton
CSR1114/R45	Hybrid	PostFDR	Experimental hybrid
Tx3042xTx2737	Hybrid	PostFDS	Experimental hybrid
B35	Lines	Stay green (charcoal rot resistant)	Public inbred
SC35	Lines	Stay green (charcoal rot resistant)	Breeding material
SC599	Lines	Stay green (Stalk rot resistant)	Breeding material
Tx2783	Lines	Non stay green	Public inbred
Tx430	Lines	Non stay green	Public inbred
Tx7000	Lines	Non stay green (charcoal rotsusceptible)	Public inbred

PreFDS : Pre−flowering drought susceptible.

PreFDR: Pre−flowering drought resistant.

PostFDR : Post−flowering drought resistant.

PostFDRS: Post−flowering drought susceptible.

Table 3**.** Details of various cultural practices used in conducting the experiments in Kansas in 2010 and 2011.

Location	Planting date	Nitrogen application	sampling at stage 3	sampling at stage 6	Sampling at stage 9	Harvesting	Herbicides application
…….. 2010 ……							
Manhattan (Unit 1)	May 25	June 9 (14)	July 4 (40)	July 2 (64)	August 25 (92)	Oct.10 (139)	June 25
Manhattan (Unit 7)	June 23	July 22 (13)	August 3 (42)	August 24 (63)	August 28 (98)	Nov. 3 (135)	June 24
Ottawa	May 28	June 13 (17)	July 9 (43)	August 3 (68)	August 4 (100)	Sept 29 (126)	May 29
Hays	June 11	June 18 (8)	July 24 (44)	August 16 (67)	Sept 18 (100)	Nov 11 (155)	June 6
…… 2011 ……							
Manhattan (Unit 1)	June 6	June 22 (16)	August 2 (37)	August 6 (61)	Sept. 27 (114)	Oct 27 (143)	June 6
Manhattan (Unit 7)	June 7	June 22 (15)	August 2 (37)	August 8 (64)	Sept. 30 (116)	Oct 18 (134)	June 7
Ottawa	June 14	July 8 (14)	August 8 (37)	August 18 (63)	Oct. 7 (115)	Nov 11 (140)	May 5

Figures in parenthesis represent days after planting.

Table 4**.** Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Manhattan (Unit 1), Kansas, 2010**.**

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	43.6ef	51.7def	42.7cd	0.73	0.76	0.74
26056	46.5dc	53.4bdc	43.0dc	0.73	0.76	0.74
95207	46.0dc	51.1edf	44.2dc	0.73	0.76	0.74
99480	41.6f	48.9f	41.8d	0.74	0.76	0.74
CSR1114/R45	46.4cd	55.2abc	45.4bc	0.72	0.76	0.74
Tx3042xTx2737	49.6ab	52.1cde	44.2dc	0.74	0.76	0.74
Inbred lines						
B35	49.1b	57.9a	50.4a	0.74	0.76	0.74
SC35	49.5ab	55.6ab	50.6a	0.73	0.76	0.70
SC599	51.6a	55.7ab	49.1a	0.73	0.76	0.74
Tx2783	45.8cd	51.1edf	41.9d	0.72	0.76	0.75
Tx430	47.9bc	55.3ab	48.0ab	0.73	0.70	0.74
Tx7000	45.4de	49.9ef	42.6dc	0.73	0.76	0.74
N levels (N)						
0	43.4c	50.2c	40.6c	0.76	0.73	0.74
45	47.8b	53.5b	44.6b	0.76	0.73	0.75
90	49.5a	55.7a	49.8a	0.76	0.73	0.74
F test and contrast probability…… Pr > F…….. ……..						
Genotypes	***	***	***	NS	NS	NS
N levels	***	***	***	NS	NS	NS
G × N	NS	NS	***	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 5. Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Manhattan (Unit 7), Kansas, 2010.

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	49.6ab	52.3c	46.5cde	0.63abcd	0.74	0.69c
26056	46.7de	51.2cd	45.7def	0.64abcd	0.74	0.69c
95207	48.1bcd	52.5c	48.0bc	0.64abcd	0.75	0.69c
99480	45.9e	49.0e	43.7f	0.62bdc	0.74	0.69c
CSR1114/R45	47.3cde	50.0de	47.1cd	0.66ac	0.75	0.70bc
Tx3042xTx2737	47.4cde	49.9de	47.6bcd	0.67ab	0.74	0.73a
Inbred lines						
B35	48.1bcd	55.9a	49.2ab	0.69a	0.73	0.73a
SC35	50.2a	55.8a	50.8a	0.66abc	0.73	0.70bc
SC599	49.6ab	55.0ab	50.8a	0.61cd	0.74	0.70bc
Tx2783	48.2bcd	52.5c	44.7ef	0.62bcd	0.74	0.72ab
Tx430	48.8abc	54.7ab	47.9bc	0.65a	0.73	0.71bc
Tx7000	47.9cd	54.1b	49.3ab	0.66abc	0.73	0.73a
N levels (N)						
0	49.2a	57.0a	49.5a	0.65	0.74	0.71
45	47.7b	52.4b	47.4b	0.64	0.74	0.71
90	47.5b	51.8b	45.9c	0.64	0.74	0.71
F test probability	.....	.....	Pr > F	.....	.....	.....
Genotypes	***	***	***	***	NS	*
N levels	***	***	***	NS	NS	NS
G × N	**	**	**	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 6. Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Ottawa, Kansas, 2010.

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	37.3e	41.6f	35.7ef	0.71	0.73	0.63d
26056	39.3cbd	44.4d	35.5ef	0.72	0.73	0.65bcd
95207	40.3b	46.3b	36.4def	0.70	0.74	0.65bcd
99480	37.9de	42.3ef	31.9g	0.72	0.73	0.64cd
CSR1114/R45	39.8cb	45.6bc	37.7bcde	0.70	0.73	0.66bc
Tx3042xTx2737	38.5cde	44.7bcd	39.4bc	0.71	0.72	0.64cd
Inbred lines						
SC35	41.8a	48.9a	40.3ba	0.69	0.74	0.68a
SC599	39.3bcd	43.6de	38.4bcd	0.72	0.75	0.64cd
Tx2783	37.6e	46.5b	37.4cde	0.68	0.74	0.66ab
Tx430	42.6a	48.8a	42.3a	0.70	0.74	0.67ab
Tx7000	39.2bcd	45.0bcd	39.8abc	0.70	0.75	0.65bcd
N levels (N)						
0	37.5c	42.4c	35.3b	0.71a	0.73	0.65
45	39.8b	45.6b	38.2a	0.69b	0.07	0.54
90	41.5a	47.7a	39.6a	0.71a	0.74	0.65
F test probability……			Pr > F…….			
Genotypes	***	***	***	NS	NS	**
N levels	***	***	***	*	NS	NS
G × N	***	*	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 7**.** Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Hays, Kansas, 2010.

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	47.9de	55.2d	46.5cd	0.73	0.75bc	0.75
26056	49.6bdec	56.2cd	48.3cb	0.73	0.76bc	0.75
95207	48.8cde	56.8bcd	45.8de	0.71	0.75c	0.74
99480	46.6e	52.9e	43.8fe	0.72	0.77ba	0.74
CSR1114/R45	50.3bdc	56.9bcd	48.9b	0.72	0.76bac	0.76
Tx3042xTx2737	49.6bcd	56.7bcd	46.8bcd	0.74	0.76bc	0.76
Inbred lines						
B35	50.3abcd	58.6ab	51.5a	0.73	0.78a	0.76
SC35	51.1ab	59.6a	52.8a	0.73	0.77ab	0.75
SC599	52.6a	57.3bc	52.8a	0.73	0.76ba	0.75
Tx2783	50.6abc	51.6e	41.5f	0.72	0.75bc	0.74
Tx430	48.9cde	52.6e	46.8bcd	0.74	0.76bc	0.75
Tx7000	48.6cde	55.0d	44.6de	0.72	0.77ba	0.75
N levels (N)						
0	48.3b	54.9c	44.5b	0.72	0.76	0.75
45	49.8b	56.0b	48.1a	0.73	0.76	0.75
90	52.3a	58.9a	49.1a	0.72	0.76	0.75
F test probability……			Pr > F……			
Genotypes	**	***	***	NS	*	NS
N levels	*	***	***	NS	NS	NS
G × N	NS	NS	**	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 8**.** Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Manhattan (Unit 1), Kansas, 2011.

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	49.6a	52.8de	43.0bc	0.75ab	0.72	0.72
26056	50.4a	56.0ab	46.0ab	0.76ab	0.68	0.67
95207	49.0ab	54.0bcd	44.2abc	0.77a	0.67	0.72
99480	49.2a	53.0de	43.0bc	0.75ab	0.73	0.67
CSR1114/R45	49.6a	56.4a	46.3a	0.73bc	0.73	0.71
Tx3042xTx2737	49.7a	55.0ab	44.6abc	0.72bc	0.66	0.70
Inbred lines						
B35	50.0a	57.1a	46.3ab	0.75abc	0.69	0.67
SC35	49.5a	56.0ab	44.5abc	0.72bc	0.69	0.69
SC599	44.7c	47.5f	42.8bc	0.72bc	0.68	0.67
Tx2783	49.6a	53.2cde	45.9ab	0.71c	0.72	0.71
Tx430	49.0ab	55.3ab	45.5abc	0.75ab	0.71	0.72
Tx7000	47.4b	51.6e	42.5c	0.73bc	0.73	0.70
N levels (N)						
0	48.0b	52.6b	42.9b	0.73	0.69	0.69
45	49.0a	54.0b	44.4b	0.74	0.71	0.70
90	49.9a	55.3a	46.4a	0.75	0.70	0.69
F test probability……..…… Pr > F……..						
Genotypes	**	**	*	*	NS	NS
N levels	**	**	**	NS	NS	NS
G × N	NS	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 9. Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Manhattan (Unit 7), Kansas, 2011**.**

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	49.2c	51.1f	42.2e	0.72	0.71	0.71
26056	50.3bc	56.2bc	47.5abc	0.69	0.69	0.69
95207	50.6bc	53.4def	46.2bcd	0.71	0.70	0.68
99480	49.7c	55.6bcd	46.4bcd	0.71	0.71	0.66
CSR1114/R45	50.0bc	54.5cd	47.8abc	0.71	0.71	0.68
Tx3042xTx2737	49.6c	56.4bc	45.8cd	0.74	0.71	0.70
Inbred lines						
B35	52.8a	59.8a	49.3a	0.71	0.68	0.69
SC35	51.7ab	61.3a	48.7ab	0.69	0.66	0.72
SC599	46.6d	48.4g	41.4e	0.71	0.70	0.66
Tx2783	49.9bc	53.7de	44.9d	0.70	0.71	0.69
Tx430	50.3bc	57.0b	45.8cd	0.73	0.69	0.72
Tx7000	46.3d	51.6ef	41.2e	0.70	0.68	0.68
N levels (N)						
0	48.4b	54.3	44.5b	0.71	0.71a	0.66b
45	49.6a	55.2	45.9a	0.71	0.69a	0.69ab
90	50.2a	55.3	46.4a	0.71	0.67b	0.70a
F test probability…… Pr > F……						
Genotypes	**	**	**	NS	NS	NS
N levels	*	NS	NS	NS	*	*
G × N	*	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 10. Effect of genotype and nitrogen levels on physiological traits of grain sorghum grown at Ottawa, Kansas, 2011.

Treatment	SPAD Vegetative (unitless)	SPAD Flowering (unitless)	SPAD Maturity (unitless)	Fv/Fm Vegetative (unitless)	Fv/Fm Flowering (unitless)	Fv/Fm Maturity (unitless)
Genotypes (G)						
Hybrids						
23012	43.2abcd	45.8e	38.0d	0.73	0.76	0.76
26056	43.2abcd	50.8abc	42.6ab	0.72	0.76	0.76
95207	43.7abc	48.0d	41.2bcd	0.71	0.75	0.74
99480	41.6cd	47.9d	39.5bcd	0.72	0.77	0.74
CSR1114/R45	44.5a	52.2ab	44.0a	0.72	0.77	0.76
Tx3042xTx2737	44.3ab	50.2bc	41.3abc	0.74	0.77	0.76
Inbred lines						
B35	43.8abc	50.1bcd	42.9ab	0.73	0.78	0.76
SC35	45.1a	51.2abc	41.4abcd	0.74	0.77	0.76
SC599	38.9e	44.4e	38.3cd	0.73	0.77	0.75
Tx2783	41.0de	49.6cd	41.9ab	0.72	0.76	0.75
Tx430	44.6a	52.7a	44.4a	0.75	0.76	0.75
Tx7000	42.0bcd	44.5e	40.4bcd	0.73	0.77	0.76
N levels (N)						
0	42.6	47.5b	38.9b	0.73	0.77	0.76
45	43.1	49.4a	42.4a	0.74	0.77	0.75
90	43.3	49.9a	42.6s	0.73	0.77	0.75
F test probability……			Pr > F……			
Genotypes	**	***	*	NS	NS	NS
N levels	NS	***	**	NS	NS	NS
G × N	NS	NS	*	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 11. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Manhattan (Unit 1), Kansas, 2011.

Treatment	Plant height (cm)	Green leaves (plant^{-1})	Total leaves (plant^{-1})	Senesced (%)	Biomass vegetative (kg ha^{-1})	Biomass flowering (kg ha^{-1})	Biomass maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	115	7.0c	14.0c	50.9ab	2504cd	5696cde	11593bc
26056	114	8.0b	15.0b	48.2abcd	2689c	5885dc	12356bac
95207	113	8.0b	14.0c	48.2abcd	1999def	4842f	10313d
99480	114	8.0b	16.0a	50.2abc	3352a	6269c	13237a
CSR1114/R45	118	8.0b	15.0b	54.3a	3270ab	5988c	12798ab
Tx3042xTx2737	116	8.0b	15.0b	43.6cde	1833f	5109def	11147cd
Inbred lines							
B35	116	8.0b	16.0a	39.7e	1966ef	7880b	7219f
SC35	114	9.0a	16.0a	47.6abcd	1606f	5030ef	7219f
SC599	115	9.0a	16.0a	45.9bcde	2002def	4538f	8416ef
Tx2783	114	9.0a	15.0b	51.3ab	2756bc	9714a	12014bc
Tx430	116	8.0b	14.0c	43.0de	1812f	5780cde	7561f
Tx7000	118	9.0a	16.0a	46.8bcd	2392cde	5662dce	11186dc
N levels (N)							
0	114	7.0	14.0c	46.7b	2243b	4929c	8650c
45	115	7.0	15.0b	48.8a	2292ab	6150b	10701b
90	116	7.0	16.0a	47.0a	2511a	7001a	12342a
F test probability…… Pr > F……							
Genotype	NS	**	**	**	***	***	***
N levels	NS	NS	**	*	**	***	***
G × N	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 12. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Manhattan (Unit 7), Kansas, 2011.

Treatment	Plant height (cm)	Green leaves (plant^{-1})	Total leaves (plant^{-1})	Senesced (%)	Biomass Vegetative (kg ha^{-1})	Biomass Flowering (kg ha^{-1})	Biomass Maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	106d	7.3bc	13.1b	45.0bcd	2869cd	8908cde	1612b
26056	119a	7.4bc	12.6b	41.2c	2795cd	9150cd	17303ba
95207	91.8e	7.0cd	12.3b	42.2c	2756cd	8358def	12973cd
99480	117a	7.5bc	12.8b	44.0bc	3421ab	11469a	17601a
CSR1114/R45	110c	7.0c	13.0b	38.7c	3569a	10272b	17963a
Tx3042xTx2737	119a	7.5bc	12.6b	44.5bc	3042bc	7879fg	13641c
Inbred lines							
B35	107cd	7.2bc	12.2b	40.3c	1683g	7047gh	9496f
SC35	106d	8.1ab	13.0b	40.0c	2232ef	7763fgh	10173f
SC599	106d	8.6a	14.2a	38.7c	2469def	9379bc	11962d
Tx2783	119a	7.4bc	12.6b	42.8c	2631de	9549bc	13850c
Tx430	118a	6.0de	12.5b	50.5ab	1763g	6886h	10495ef
Tx7000	112b	5.8e	13.0b	56.5a	2085fg	8107ef	11904de
N levels (N)							
0	110b	6.3b	12.5	48.9a	2607	9432a	15264a
45	110b	7.6a	12.9	40.5b	2674	8857b	13512b
90	112a	7.7a	13.1	41.7b	2547	7903c	12095c
F test probability…… Pr > F……							
Genotype	*	**	**	**	***	***	***
N levels	*	*	NS	**	NS	***	***
G × N	NS	NS	NS	*	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 13. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Ottawa , Kansas, 2011.

Treatment	Plant height (cm)	Green leaves (plant^{-1})	Total leaves (plant^{-1})	Senesced (%)	Biomass Vegetative (kg ha^{-1})	Biomass Flowering (kg ha^{-1})	Biomass Maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	117b	8.0b	14.0c	42.8a	2496abc	6126c	7939ab
26056	120b	9.0a	16.0a	43.7a	2807a	7225a	8563ab
95207	100gf	9.0a	15.0b	40.0b	2626ab	5868c	7894ab
99480	125b	8.0b	14.0c	42.0b	2829a	7861a	8868a
CSR1114/R45	120b	8.0b	14.0c	42.9a	2896a	6991ab	8821a
Tx3042xTx2737	111cd	8.0b	15.0b	46.7a	2053cde	4859de	5869de
Inbred Lines							
SC35	108def	8.0b	14.0c	42.9b	1822e	4714de	6140d
SC599	95.9g	8.0b	14.0c	42.9b	1664ef	6289bc	6359d
Tx2783	130a	8.0b	14.0c	42.9b	1914de	6018c	7538bc
Tx430	103ef	8.0b	15.0b	46.7a	1239f	4057e	4960e
Tx7000	110ed	8.0b	14.0c	42.9b	2323bcd	5461cd	6864d
N levels (N)							
0	109b	7.0c	13.0c	46.2b	2057b	5248c	6279c
45	113b	8.0b	15.0b	46.7b	2198b	6118b	7418b
90	115a	10.0a	16.0a	37.5a	2473a	6495a	8203a
F test probability…….. ……. Pr > F……..							
Genotype	***	**	**	*	***	***	***
N levels	*	*	*	***	**	***	***
G × N	NS	NS	NS	**	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 14. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Hays, Kansas, 2010.

Treatment	Plant height (cm)	Green leaves (plant^{-1})	Total leaves (plant^{-1})	Senesced (%)	Biomass Vegetative (kg ha^{-1})	Biomass Flowering (kg ha^{-1})	Biomass Maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	92.5de	8.0d	14.0c	46.5bc	3083cd	6948d	10320ef
26056	97.2bc	9.0c	14.0c	41.3cd	3655ab	9712a	14012ba
95207	88.5e	8.0d	13.0d	40.3cde	3168bcd	8137c	11763cde
99480	94.3dce	9.0c	15.0b	55.1a	3791a	8687bc	15257a
CSR1114/R45	95.8dc	10.0b	15.0b	27.3fg	3544abc	9513ab	13570bac
Tx3042xTx2737	102ab	8.0d	14.0c	39.0de	2709de	6805ed	10969edf
Inbred lines							
B35	102ab	11.0a	16.0a	24.6g	2369ef	6027ef	12341bcd
SC35	95.8cd	11.0a	16.0a	27.0fg	1826g	3823i	5624h
SC599	95.5cd	10.0b	14.0a	33.5ef	1845g	4824gh	7484gh
Tx2783	103a	11.0a	16.0a	43.9cd	2109fg	4654hi	9387fg
Tx430	96.2cd	11.0a	15.0b	25.0g	2244efg	4721ghi	7531gh
Tx7000	95.7cd	8.0d	14.0c	52.9ab	2502ef	5587fg	10407def
N levels (N)							
0	97.6	9.0b	16.0	37.1	2702	5686c	8708c
45	96.0	10.0a	16.0	37.1	2782	6753b	11294b
90	95.9	10.0a	16.0	39.4	2728	7510a	12476a
F test probability…… Pr > F……..							
Genotype	***	***	***	***	***	***	***
N levels	NS	*	NS	NS	NS	***	***
G × N	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 15. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Manhattan (Unit 1), Kansas, 2011.

Treatment	Plant (cm)	Green leaves (plant^{-1})	Total (plant^{-1})	Senesced %	Biomass Vegetative (kg ha^{-1})	Biomass Flowering (kg ha^{-1})	Biomass Maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	104bc	6.6bc	13.3cd	50.2abc	2041a	6328bc	12502ab
26056	116bc	6.7bc	13.3cd	49.1abc	2049a	6506abc	11169bcde
95207	93.8c	6.0c	13.0e	53.7a	2081a	6104c	10869cde
99480	120b	8.2a	14.0a	44.3d	1916ab	7458a	13124a
CSR1114/R45	108bc	6.6bc	13.8bc	52.5a	2051a	6621abc	11843abc
Tx3042xTx2737	121b	6.3c	13.6bcd	52.0a	1932ab	5890c	11690abcd
Inbred lines							
B35	109bc	6.5bc	13.7bcd	44.9cd	1654bc	6485abc	10143def
SC35	118bc	8.1a	14.8a	38.1e	1327d	6259bc	7924g
SC599	111bc	8.9a	14.5a	52.8a	1733bc	7163ab	8527fg
Tx2783	152a	7.2b	14.1ab	49.3abc	1611c	7549a	9740ef
Tx430	118bc	7.2b	13.5bcd	46.bcd	1636c	6069c	9121fg
Tx7000	116bc	6.1c	12.6e	51.4ab	1823abc	6165bc	9862ef
N levels (N)							
0	120.5	7.0	13.9	49.7	1788	5613c	9837b
45	114.0	7.1	13.8	48.2	1848	6681b	10811a
90	113.4	7.0	13.5	48.2	1827	7356a	10980a
F test probability…… Pr > F……..							
Genotype	*	**	**	**	**	*	***
N levels	NS	NS	NS	NS	NS	**	**
G × N	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 16. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Manhattan (Unit 7), Kansas, 2011.

Treatment	Plant height (cm)	Green leaves (plant^{-1})	Total leaves (plant^{-1})	Senesced (%)	Biomass Vegetative (kg ha^{-1})	Biomass Flowering (kg ha^{-1})	Biomass Maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	125a	5.8ef	13.5cd	44.2de	2058a	5459de	11530ab
26056	119b	6.7de	13.4cd	49.7cd	2155a	6173abc	11993a
95207	118bc	5.1f	12.1e	42.7e	2040ab	6177abc	11515ab
99480	117bc	7.3cd	14.5ab	50.9c	1784cd	6705a	11909a
CSR1114/R45	114cd	6.9d	13.3cd	53.1c	2047ab	6281abc	11856a
Tx3042xTx2737	105f	5.2f	12.4e	51.2c	1844c	6336abc	10231bc
Inbred lines							
B35	116bc	7.5cd	13.7bc	62.8a	1337ef	5096e	6849d
SC35	111d	9.3a	14.9a	61.6ab	1217f	5776bc	6214d
SC599	110de	8.7ab	14.1abc	55.9bc	1643d	6736a	9806c
Tx2783	106ef	8.0bc	14.4ab	51.1c	1421ef	6559ab	12021a
Tx430	105f	6.6de	12.7de	40.6e	1440e	5634cde	9460c
Tx7000	91.6g	5.8ef	13.3cd	44.4de	1854bc	5976abcd	9643c
N levels (N)							
0	111	6.5b	13.0	50.0a	1738	5345c	9807b
45	111	7.1a	13.5	45.0c	1717	5952b	9741b
90	112	7.2a	13.6	47.7b	1755	6931a	11209a
F test probability…….. Pr > F……							
Genotype	**	**	**	*	**	**	**
N levels	NS	*	NS	**	NS	**	**
G × N	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 17. Effect of genotype and nitrogen levels on growth traits of grain sorghum grown at Ottawa, Kansas, 2011.

Treatment	Plant height (cm)	Green leaves (plant^{-1})	Total leaves (plant^{-1})	Senesced (%)	Biomass Vegetative (kg ha^{-1})	Biomass Flowering (kg ha^{-1})	Biomass Maturity (kg ha^{-1})
Genotypes (G)							
Hybrids							
23012	96.8cd	6.1de	12.3def	50.6a	1197ab	5335cd	6647bc
26056	99.0abc	6.7de	11.6f	42.9b	1173ab	5449cd	6471c
95207	80.9e	5.8de	11.4f	49.6a	1285a	5355cd	6544c
99480	109ab	7.0cde	13.4bcde	47.8a	965cd	5554.1cd	7265abc
CSR1114/R45	103abc	7.3bcd	12.7cdef	42.5b	1118b	5449cd	9123ab
Tx3042xTx2737	105abc	6.5de	12.8ef	46.2ab	1078bc	4381d	6715bc
Inbred lines							
B35	83.7de	8.3abc	14.4ab	42.2b	1052bc	7791a	7335abc
SC35	96.7bcd	9.2a	15.0a	38.5bc	884d	8116a	8940ab
SC599	104abc	8.5ab	14abc	39.3bc	1134ab	6995ab	9482a
Tx2783	109abc	7.2bcd	13.6abcd	46.3b	1101b	6466bc	6734bc
Tx430	105abc	6.9de	12.8cdef	45.6b	883d	4971d	6803bc
Tx7000	110a	7.2bcd	13.8abc	47.1ab	1164ab	5505cd	8464abc
N levels (N)							
0	97.4	6.6b	13.0	48.7b	1083	5142b	6476b
45	103	7.0b	12.9	45.8b	1111	6267a	8381a
90	100	7.9a	13.3	40.1a	1065	6433a	7773a
F test probability…… Pr > F……							
Genotype	**	**	**	*	**	***	*
N levels	NS	*	NS	*	NS	***	**
G × N	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 18. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Manhattan (Unit 1), Kansas, 2010.

Treatment	Grain yield (kg ha^{-1})	Harvest index (ratio)	200 kernel wt. (g)	Kernel number (m^{-2})
Genotypes (G)				
Hybrids				
23012	4464ab	0.41ab	4.53cd	17028abc
26056	5106a	0.42bc	4.64cd	20913a
95207	4027bc	0.47a	4.58cd	17829ab
99480	4863a	0.39c	4.88bc	19048ab
CSR1114/R45	477ba	0.25e	5.11ab	17774ab
Tx3042xTx2737	4020bc	0.39c	4.47d	15856bc
Inbred Lines				
B35	2518ef	0.28d	4.43d	8820de
SC35	1420g	0.29d	4.03e	6137e
SC599	2674ef	0.29d	4.66cd	12996cd
Tx2783	3135de	0.40ab	4.07e	15668bc
Tx430	2336f	0.29d	5.36a	9208de
Tx7000	3422de	0.32d	4.77bcd	15228bc
N levels (N)				
0	3373b	0.33	4.79	15098a
45	3575ab	0.35	4.69	14949b
90	3836a	0.35	4.64	14079c
F test probability……		Pr > F……..		
Genotype	***	***	***	***
N levels	*	NS	NS	*
G × N	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 19. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Manhattan (Unit 7), Kansas, 2010.

Treatment	Grain yield ($kg\ ha^{-1}$)	Harvest (ratio)	200 kernel wt. (g)	Kernel number (m^{-2})
Genotypes (G)				
Hybrids				
23012	6563a	0.50ab	4.65f	27961ab
26056	6779a	0.50ab	5.27c	25745ab
95207	5239d	0.44cd	5.38c	19137bcde
99480	6608a	0.50ab	4.93de	27353a
CSR1114/R45	6645a	0.46bc	5.73b	23642bc
Tx3042xTx2737	5968b	0.49abc	5.27c	21233bcd
Inbred Lines				
B35	2749g	0.27f	5.14cd	10204de
SC35	1774h	0.20g	5.65b	7382e
SC599	4183e	0.35e	4.24g	18847bcde
Tx2783	6148b	0.49abc	4.71ef	25791ab
Tx430	3689g	0.39de	6.23a	12728cde
Tx7000	5545c	0.51a	4.90de	21998bcd
N levels (N)				
0	5155b	0.42	5.08b	20535
45	5259a	0.43	5.20a	20184
90	5241a	0.42	5.24a	23953
F test probability…… Pr > F…….				
Genotype	***	**	***	***
N levels	*	NS	*	NS
G × N	***	NS	*	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 20. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Ottawa, Kansas, 2010**.**

Treatment	Grain yield (kg ha^{-1})	Harvest index (ratio)	200 kernel wt. (g)	Kernel number (m^{-2})
Genotypes (G)				
Hybrids				
23012	2258a	0.33ab	4.98cd	9067b
26056	2419a	0.31ab	5.50ab	8793b
95207	2522a	0.34ab	5.52ab	9102b
99480	2767a	0.33ab	4.91cd	11361a
CSR1114/R45	2253a	0.30b	5.20bc	8689b
Tx3042xTx2737	2606a	0.29b	5.47ab	9492ab
Inbred Lines				
SC35	594c	0.29b	5.38ab	2326d
SC599	1371b	0.18c	4.86d	5371c
T 2783	622c	0.36a	4.47e	2806d
Tx430	1431b	0.35a	5.65a	5137c
Tx7000	1569b	0.29b	5.38ab	5892c
N levels (N)				
0	1536c	0.25c	5.28	5807c
45	1852b	0.29b	5.11	7123b
90	2266a	0.35a	5.24	8352a
F test probability…… Pr > F……				
Genotype	***	***	***	***
N levels	***	***	NS	***
G XN	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 21. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Hays, Kansas, 2010.

Treatment	Grain yield (kg ha^{-1})	Harvest index (ratio)	200 kernel wt. (g)	Kernel number (m^{-2})
Genotypes (G)				
Hybrids				
23012	3877cb	0.41b	5.12def	16288cd
26056	4867a	0.35cd	5.57ab	19169b
95207	3859cb	0.49a	5.58ab	18800bc
99480	5229a	0.42b	5.39bc	22887a
CSR1114/R45	4195b	0.30ed	5.41bc	11299f
Tx3042xTx2737	3786cb	0.37bc	5.76a	20448ab
Inbred Lines				
B35	3383c	0.24f	5.18cde	8399g
SC35	995e	0.42b	5.29cd	1293h
SC599	2764d	0.39bc	4.95ef	11056f
Tx2783	3352c	0.39bc	4.92f	14474de
Tx430	1315e	0.26e	5.75a	7252g
Tx7000	3647c	0.39bc	5.68a	14191df
N levels (N)				
0	3507b	0.32c	5.35	13142b
45	3633b	0.36b	5.43	14169b
90	3369a	0.43a	5.37	15843a
F test probability……. Pr > F…… …..				
Genotype	***	***	**	***
N levels	*	*	NS	**
G × N	*	*	NS	*

*, **, *** Significantly difference at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 22. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Manhattan (Unit 1), Kansas, 2011.

Treatment	Grain yield (kg ha^{-1})	Harvest index (ratio)	200 kernel wt. (g)	Kernel number (m^{-2})
Genotypes (G)				
Hybrids				
23012	2934cd	0.35ab	5.81bc	9513de
26056	3798b	0.31bc	5.95ab	12194bc
95207	3568b	0.37a	5.96ab	12648b
99480	4749a	0.36ab	5.35d	17812a
CSR1114/R45	1671f	0.28cd	6.26a	5539f
Tx3042xTx2737	3115c	0.35ab	4.6e	10099cde
Inbred Lines				
B35	987g	0.23d	5.25d	3764fg
SC35	1391fg	0.23d	5.62bcd	4483fg
SC599	2156e	0.26cd	5.39cd	8692e
Tx2783	2585de	0.37a	6.09ab	10925bcd
Tx430	947g	0.29c	6.26a	3145g
Tx7000	1407fg	0.31bc	6.31a	4749fg
N levels (N)				
0	2289b	0.32	5.60b	8249c
45	2422ab	0.31	5.90a	8414b
90	2617a	0.30	5.73ab	9226a
F test probability……		Pr > F……		
Genotype	***	***	**	***
N levels	*	NS	**	*
G × N	***	NS	**	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 23. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Manhattan (Unit 7), Kansas, 2011.

Treatment	Grain yield (kg ha^{-1})	Harvest index (ratio)	200 kernel wt. (g)	Kernel number (m^{-2})
Genotypes (G)				
Hybrids				
23012	2738d	0.34cd	5.05cde	11067c
26056	4293ab	0.30ef	5.84b	13027bc
95207	3900bc	0.37ab	5.07cde	15625ab
99480	4592a	0.40a	5.04cde	17911a
CSR1114/R45	1451ef	0.28fg	6.00ab	5882de
Tx3042xTx2737	3575c	0.37ab	5.33c	13401bc
Inbred Lines				
B35	988f	0.20i	5.05cde	3833e
SC35	2029e	0.24h	5.30cd	6882de
SC599	1838e	0.28fg	4.92de	7608d
Tx2783	3370c	0.36bc	4.81e	13896b
Tx430	1797e	0.31de	5.79b	6584de
Tx7000	1751e	0.26gh	6.24a	6067de
N levels (N)				
0	2490b	0.32	5.19b	9551b
45	2787ab	0.31	5.39ab	10644a
90	2803a	0.30	5.53a	10250a
F test probability……		Pr > F……..		
Genotype	***	***	**	**
N levels	*	NS	**	NS
G × N	***	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 24. Effect of genotype and nitrogen levels on yield and components of yield traits of grain sorghum grown at Ottawa, Kansas, 2011.

Treatment	Grain yield (kg ha^{-1})	Harvest index (ratio)	200 kernel (g)	Kernel (m^{-2})
Genotypes (G)				
Hybrids				
23012	2715c	0.50a	5.39b	10078e
26056	3654b	0.47ab	5.15bcd	14294bc
95207	1319e	0.50a	6.16a	3958g
99480	4468a	0.46abc	4.70ef	19066a
CSR1114/R45	3349b	0.51a	5.33bc	12612cd
Tx3042xTx2737	3284b	0.44bc	6.16a	10736de
Inbred Lines				
B35	1906d	0.29e	5.61b	3116gh
SC35	1607de	0.33de	5.43b	1089h
SC599	2067d	0.36d	4.83de	9113e
Tx2783	3289b	0.47abc	4.29f	15413b
Tx430	1929d	0.42c	6.12a	6371f
Tx7000	3337b	0.46abc	4.96cde	13606bc
N levels (N)				
0	2558b	0.43	5.29	9315b
45	2786a	0.42	5.34	9851ab
90	2887a	0.45	5.40	10696a
F test probability……		Pr > F……		...
Genotype	***	***	***	**
N levels	*	NS	NS	*
G × N	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 25. Nitrogen uptake at flowering stage at Manhattan (Unit 7), Kansas, 2010**.**

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Total plant N (kg ha^{-1})
Genotypes (G)			
Hybrids			
23012	64.5ed	53.5abc	118ab
26506	79.1ab	59.0ab	138a
95207	62.6ed	63.8ab	12ab
99480	86.5a	52.0abcd	139a
CSR1114/R45	77.3abc	61.4ab	139a
Tx3042xTx2737	63.7ed	60.0ab	124ab
Inbred lines			
B35	57.2e	40.2cd	97.5c
SC35	59.0ed	38.1d	97.1c
SC599	66.1ed	55.0ab	121ab
Tx2783	66.8cde	61.0ab	128ab
Tx430	62.3ed	50.8bcd	113bc
Tx7000	69.9bcd	65.9a	136a
N levels (N)			
0	64.3b	49.2b	119b
45	66.9ab	52.0b	114b
90	72.6a	63.9a	137a
F test and contrast probability….. Pr > F…….**.....**			
Genotypes	**	**	**
N levels	*	**	**
G × N	NS	NS	NS
Linear on N	NS	NS	NS
Quadratic on N	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 26. Nitrogen uptake at physiological maturity at Manhattan (Unit 7), Kansas, 2010.

T**reatment**	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Grain N (kg ha^{-1})	Total plant (kg ha^{-1})
Genotypes				
Hybrids				
23012	31.0bcd	15.6c	91.2cb	137cde
26506	37.1abc	21.8a	108b	166b
95207	39.0ab	21.5a	93.6cb	154bc
99480	29.7bed	18.8c	107b	155bc
CSR1114/R45	44.1a	20.2a	135a	199a
Tx3042xTx2737	23.4de	14.8c	102b	141cde
Inbred lines				
B35	20.5e	13.0c	94.4bc	128def
SC35	31.1bcd	18.8c	53.7e	104f
SC599	36.5abc	15.4c	65.7ed	118ef
Tx2783	37.4abc	27.3a	72.0cde	137cde
Tx430	22.2ed	18.5c	84.6bcd	125ef
Tx7000	29.0cde	16.2c	107b	153bcd
N levels (N)				
0	28.5b	14.8b	72.7b	116c
45	36.3a	23.0a	104a	163a
90	30.5b	17.7b	101a	149b
F test and contrast probability……. Pr > F…….....				
Genotypes	**	*	**	**
N levels	**	**	**	*
G × N	*	*	NS	*
Linear on N	NS	NS	NS	NS
Quadratic on N	NS	**	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 27. Nitrogen uptake at flowering stage at Ottawa, Kansas, 2010**.**

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Total plant N (kg ha^{-1})
Genotypes (G)			
Hybrids			
23012	18.8ab	16.9bcd	35.7abcd
26506	19.4ab	20.3ab	39.8abc
95207	15.2cd	13.1d	28.4f
99480	21.4a	20.1ab	41.5ab
CSR1114/R45	19.3ab	22.9a	42.7a
Tx3042xTx2737	16.6bcd	17.8bcd	34.4def
Inbred lines			
SC35	16.5bcd	18.5abc	35.0bcde
SC599	14.3cd	17.4bcd	31.8def
Tx2783	17.2bcd	20.1ab	37.3abcd
Tx430	14.0d	15.0cd	29.0ef
Tx7000	17.6bc	21.3ab	38.9abc
N levels (N)			
0	18.2	17.6b	35.9
45	16.7	17.4b	34.2
90	17.0	20.4a	37.5
F test and contrast probability…… Pr > F……..			
Genotypes	**	*	**
N levels	NS	NS	NS
G × N	NS	NS	NS
Linear on N	NS	NS	NS
Quadratic on N	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 28. Nitrogen uptake at physiological maturity at Ottawa, Kansas, 2010.

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Grain N (kg ha^{-1})	Total plant (kg ha^{-1})
Genotypes (G)				
Hybrids				
23012	10.7bcd	8.4b	29.3ab	48.4ab
26506	11.0abcd	9.0b	33.5a	53.6a
95207	10.9abcd	8.8b	31.4ab	51.2ab
99480	11.6abc	9.4ab	34.3a	55.4a
CSR1114/R45	12.4ab	9.7ab	29.9ab	52.1ab
Tx3042xTx2737	9.1cde	9.7ab	20.4cd	39.3cd
Inbred lines				
SC35	13.5a	11.4a	25.2bc	50.1ab
SC599	8.6de	7.7bc	14.2d	30.6d
Tx2783	10.6bcd	9.5ab	34.0a	54.2a
Tx430	11.0abcd	6.1c	17.6d	34.8dc
Tx7000	7.8e	7.5bc	28.0ab	43.4bc
N levels (N)				
0	10.4	8.4	21.9c	40.8b
45	10.2	8.6	26.3b	45.2b
90	11.4	9.5	33.0a	54.0a
F test and contrast probability…… Pr > F……....				
Genotypes	**	**	***	**
N levels	NS	NS	**	**
G × N	NS	NS	NS	NS
Linear on N	NS	NS	NS	NS
Quadratic on N	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 29. Nitrogen uptake at flowering stage at Manhattan (Unit 7), Kansas, 2011.

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Total plant N (kg ha^{-1})
Genotypes (G)			
Hybrids			
23012	50.2c	30.8d	81.1cd
26506	58.8ab	32.4bcd	89.0abcd
95207	53.1abc	36.9abcd	90.0abcd
99480	60.5a	40.8ab	101a
CSR1114/R45	57.1ab	32.1bcd	85.1bcd
Tx3042xTx2737	50.7bc	40.5abc	86.6bcd
Inbred lines			
B35	45.4c	31.5bcd	77.3d
SC35	45.5c	42.4a	88.3acd
SC599	53.0abc	37.2bcd	93.2abc
Tx2783	53.9abc	45.1a	96.9ab
Tx430	50.7bc	31.8cd	79.7cd
Tx7000	53.6abc	41.6ab	95.3ab
N levels (N)			
0	40.3c	31.3c	71.8c
45	53.4b	36.0b	87.1b
90	64.4a	43.5a	107a
F test and contrast probability… Pr >…….			
Genotypes	*	**	*
N levels	**	**	NS
G × N	NS	NS	NS
Linear on N	**	**	**
Quadratic on N	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 30. Nitrogen uptake at physiological maturity at Manhattan (Unit 7), Kansas, 2011.

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Grain N (kg ha^{-1})	Total plant (kg ha^{-1})
Genotypes (G)				
Hybrids				
23012	14.8ef	8.0e	57.7a	78.4bcd
26506	20.5cd	7.7e	51.7abc	80.0bcd
95207	19.7cde	8.9de	48.0bcd	76.7bcd
99480	19.8cde	9.4cde	58.0a	84.8abc
CSR1114/R45	29.6a	12.0cd	51.9abc	91.4a
Tx3042xTx2737	14.0f	10.8cde	46.4cd	71.3de
Inbred lines				
B35	28.4ab	19.4a	40.2def	88.0ab
SC35	24.0bc	13.0bc	36.7f	73.7cde
SC599	17.8def	8.4e	38.8ef	65.1e
Tx2783	17.6def	9.5cde	54.0ab	81.1abcd
Tx430	24.0abc	10.4cde	40.9def	74.5cde
Tx7000	22.5cd	15.8ab	45.2cde	83.5abc
N levels (N)				
0	21.4b	9.6b	40.0b	70.7b
45	22.8b	12.5a	50.8a	85.7a
90	24.1a	12.7a	51.6a	84.8a
F test and contrast probability…… Pr > F…….....				
Genotypes	***	***	***	**
N levels	*	**	***	***
G × N	NS	NS	NS	NS
Linear on N	NS	NS	**	**
Quadratic on N	*	*	*	**

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 31. Nitrogen uptake at flowering stage at Ottawa, Kansas, 2011.

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Total plant N (kg ha^{-1})
Genotypes (G)			
Hybrids			
23012	21.8ef	16.4ef	38.2ef
26506	25.5cde	14.8ef	40.2ef
95207	22.6ef	14.8ef	37.5ef
99480	24.1def	18.3def	42.4de
CSR1114/R45	23.1ef	14.9ef	38.1ef
Tx3042xTx2737	17.8f	11.6f	29.4f
Inbred lines			
B35	40.2ab	28.6ab	69.1ab
SC35	44.9a	33.9a	79.2a
SC599	32.6bc	26.2bc	58.9bc
Tx2783	30.6cd	23.6bcd	54.2cd
Tx430	24.2def	19.4cde	43.6de
Tx7000	22.9ef	16.8def	39.8ef
N levels (N)			
0	27.9	19.4	47.4
45	27.7	20.0	47.7
90	27.0	20.4	47.5
F test and contrast probability… Pr > F……			
Genotype	***	**	**
N levels	NS	NS	NS
G × N	NS	NS	NS
Linear on N	NS	NS	NS
Quadratic on N	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 32. Nitrogen uptake at physiological maturity at Ottawa, Kansas, 2011.

Treatment	Leaves N (kg ha^{-1})	Stems N (kg ha^{-1})	Grain N (kg ha^{-1})	Total plant (kg ha^{-1})
Genotypes (G)				
Hybrids				
23012	8.7cd	4.6bc	51.5a	64.6ab
26506	11.3bc	4.4bc	46.7ab	62.5ab
95207	9.8c	5.8bc	51.3a	62.5ab
99480	10.6c	4.9bc	50.3a	64.1ab
CSR1114/R45	9.8c	4.6bc	46.1b	54.4bc
Tx3042xTx2737	6.8d	4.7bc	52.0a	63.6ab
Inbred lines				
B35	18.2a	10.3a	31.6c	62.2ab
SC35	14.1b	7.1b	29.2c	51.9c
SC599	10.1c	3.9c	46.3b	61.6ab
Tx2783	9.7cd	4.6bc	47.6b	61.9ab
Tx430	9.8c	5.2bc	49.7a	63.5ab
Tx7000	10.1c	4.3bc	50.6a	65.2a
N levels (N)				
0	9.5b	4.1b	36.7b	51.4b
45	10.6b	6.0a	49.6a	64.5a
90	12.2a	6.0a	51.9a	68.6a
F test and contrast probability…… Pr > F……				
Genotype	***	*	**	*
N levels	*	NS	**	**
G × N	NS	NS	NS	NS
Linear on N	NS	NS	NS	NS
Quadratic on N	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 33. Components of nitrogen use efficiency of grain sorghum genotypes at Manhattan (Unit 7), Kansas, 2010.

Treatment	NUE (kg kg^{-1})	N Utilization Efficiency (kg kg^{-1})	N Uptake Efficiency (%)	Fertilizer N Recovery (%)	N harvest Index (%)
Genotypes (G)					
Hybrids					
23012	37.5ab	46.1ab	72.3abc	48.0b	65.4ab
26506	32.2bcde	39.5bcd	68.3bcd	52.0a	61.9abc
95207	31.6bcde	38.8bcd	64.8bcd	2.6f	59.7bcd
99480	42.6a	52.9a	82.5a	7.4f	69.7a
CSR1114/R45	34.5bc	41.6bc	71.4abc	35.2c	67.8ab
Tx3042xTx2737	36.2ab	45.5ab	65.1bcd	16.6e	71.3a
Inbred lines					
B35	37.2ab	46.7ab	74.9ab	2.1f	69.8a
SC35	25.2e	32.2d	58.2d	24.1d	51.2d
SC599	28.9cde	35.1cd	60.3dc	19.6e	54.5cd
Tx2783	26.0de	31.6d	65.2bcd	8.5f	53.9cd
Tx430	32.5bcd	42.3bc	65.1bcd	29.9d	67.4ab
Tx7000	34.0bc	42.7bc	61.6cd	17.0e	68.6ab
N levels (N)					
0	50.2a	50.2a	100.0a	0	70.2a
45	24.3b	32.8c	50.0b	26.8a	52.9b
90	25.1b	40.8b	52.5b	13.7b	67.36a
F test and contrast probability…… Pr > F…….....					
Genotypes	**	**	*	*	**
N levels	**	**	*	*	**
G × N	NS	NS	NS	NS	NS
Linear on N	NS	NS	NS	NS	NS
Quadratic on N	NS	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 34. Components of nitrogen use efficiency of grain sorghum genotypes at Ottawa (Unit 7), Kansas, 2010.

Treatment	NUE (kg kg^{-1})	N Utilization Efficiency (kg kg^{-1})	N Uptake Efficiency (%)	Fertilizer N Recovery (%)	N harvest Index (%)
Genotype (G)					
Hybrids					
23012	32.5a	51.0ab	63.4a	30.8ab	60.0a
26506	35.4a	55.8a	64.7a	29.2ab	61.4a
95207	33.3a	54.5a	63.9a	16.3b	61.0a
99480	33.9a	54.3a	64.5a	12.1c	61.4a
CSR1114/R45	32.2ab	50.2ab	63.7a	23.7ab	57.7a
Tx3042xTx2737	24.5cd	42.4cd	58.0b	11.6c	51.6b
Inbred lines					
SC35	22.3de	33.7e	62.6a	23.4ab	50.3b
SC599	18.1e	34.0e	56.1b	20.4ab	43.6c
Tx2783	27.9bc	42.7cd	65.0a	31.3ab	62.1a
Tx430	18.0e	39.5de	56.3b	15.3b	50.1b
Tx7000	26.2cd	46.2bc	62.9a	37.5a	60.5a
N levels (N)					
0	41.4a	41.4b	100.0a	0	51.8b
45	23.2b	46.8a	49.0b	27.7a	57.2a
90	18.4c	49.3a	36.8c	22.8a	60.1a
F test and contrast probability……. Pr > F……..					
P-value	***	**	*	*	**
P-value	**	**	**	NS	**
G x N	**	**	**	NS	**
Linear on N	***	***	**	NS	**
Quadratic on N	***	NS	**	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 35. Components of nitrogen use efficiency of grain sorghum genotypes at Manhattan (Unit 7), Kansas, 2011.

Treatment	NUE (kg kg^{-1})	N Utilization Efficiency (kg kg^{-1})	N Uptake Efficiency (%)	Fertilizer N Recovery (%)	N harvest Index (%)
Genotypes (G)					
Hybrids					
23012	28.4a	24.3d	71.5ab	20.1abc	70.2a
26506	24.0b	25.3d	70.9ab	19.2abc	64.5abc
95207	25.4b	26.8cd	70.4ab	14.7bcde	62.4bc
99480	26.4ab	27.2cd	70.8ab	16.0abcd	47.6e
CSR1114/R45	25.0b	35.5b	71.5ab	13.6bcde	66.6ab
Tx3042xTx2737	25.8b	27.1cd	71.6ab	10.7cde	64.9abc
Inbred lines					
B35	19.0cd	30.2c	72.6a	2.7e	53.6de
SC35	17.2d	34.5b	69.3bc	5.0de	50.8e
SC599	20.5c	35.4b	67.4c	7.3de	59.8cd
Tx2783	25.0b	35.6b	69.2bc	27.5a	65.4abc
Tx430	18.0d	36.3ab	70.4ab	22.2ab	52.5e
Tx7000	19.1cd	39.6a	71.8ab	10.0cde	54.3de
N levels (N)					
0	31.1a	31.5	100.0a	0	56.6b
45	19.8b	30.7	65.1b	14.2	59.0b
90	15.0c	32.3	46.9c	14.0	62.5a
F test and contrast probability…….. Pr > F.....					
Genotype	***	**	*	*	***
N levels	***	NS	**	NS	**
G × N	**	NS	NS	NS	NS
Linear on N	**	NS	NS	NS	NS
Quadratic on N	**	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.

Table 36. Components of nitrogen use efficiency of grain sorghum genotypes at Ottawa, Kansas, 2011.

Treatment	NUE (kg kg^{-1})	N Utilization Efficiency (kg kg^{-1})	N Uptake Efficiency (%)	Fertilizer N Recovery (%)	N harvest Index (%)
Genotypes (G)					
Hybrids					
23012	40.5abc	53.4abc	62.4abc	29.6ab	76.9ab
26506	42.6ab	43.7e	60.4c	31.9ab	75.8ab
95207	38.2cde	49.2cde	63.3abc	20.8bc	76.3ab
99480	42.9a	60.2a	62.8abc	24.2bc	76.7ab
CSR1114/R45	40.1abcd	56.2abc	62.7abc	24.5bc	75.4b
Tx3042xTx2737	37.2cde	50.6bcde	63.0a	23.9bc	81.3a
Inbred lines					
B35	19.7f	24.9f	63.8ab	18.2bc	50.6d
SC35	23.0f	29.1f	62.3abc	15.5bc	57.7c
SC599	35.8e	50.4cde	63.1abc	17.4bc	76.3ab
Tx2783	38.4bcde	55.4abc	64.5a	14.5c	75.6b
Tx430	36.3de	46.4de	60.bc4	42.2a	75.0b
Tx7000	42.3ab	57.9ab	64.4a	26.2bc	77.3ab
N levels (N)					
0	53.7a	51.4a	100.0a	0	70.7b
45	32.9b	46.8b	52.6b	30.3a	74.7a
90	22.6c	46.2b	36.0c	17.9b	73.4a
F test and contrast probability…… Pr > F.....					
Genotype	**	***	*	**	**
N levels	**	*	**	***	*
G × N	**	NS	NS	**	NS
Linear on N levels	***	NS	NS	NS	NS
Quadratic on N	**	NS	NS	NS	NS

*, **, *** Significantly different at P = 0.05, 0.01, 0.001 respectively. NS = not significant.