# Productivity and Water Use of Proso Millet Grown under Three Crop Rotations in the Central Great Plains

J.F. Shanahan,* R. L. Anderson, and B. W. Greb

## ABSTRACT

**Proso millet (*Panicum miliaceum* L.) is a shallow-rooted, short-season summer annual that is well adapted to the semiarid conditions of the western Central Great Plains. However, cropping systems for proso millet have not been well established in this region. Three proso millet cultivars were grown under three crop rotations, millet-millet (M-M), winter wheat (*Triticum aestivum* L.) -millet (W-M) and fallow-millet (F-M), for five growing seasons (1973–1977) to determine water use and productivity of the second component (proso millet) in each rotation. The research was conducted on a mesic Pachic Argiustoll soil at the Central Great Plains Research Station located near Akron, CO. Precipitation during the noncropped period for the W-M and F-M averaged 26 and 145% more, respectively, than the M-M rotation. The W-M and F-M rotations exhibited 7 and 19% more seasonal crop water use, respectively, than the M-M sequence over the 5-yr period of the study. These differences in water use resulted in the W-M and F-M rotations producing 38 and 75% more total dry matter and 50 and 116% more grain yield, respectively, than the M-M sequence. The three cultivars responded similarly to the three crop rotations. Since grain yields were low and variable for the M-M rotation and the noncropped period was quite long (86 wk) and inefficient in soil water storage for the F-M rotation, the W-M rotation appears to be the most efficient rotation of the three rotations evaluated for producing proso millet in this region.**

***Additional Index Words:* *Panicum miliaceum* L., Total dry matter yield, Harvest index.**

PROSO MILLET is a shallow-rooted, short-season summer annual that matures quickly (70–90 d) and has a relatively low water requirement (Martin et al., 1976), which contributes to its adaptation to the semiarid conditions of the western Central Great Plains where annual precipitation ranges from 300 to 500 mm (Cannell and Dregne, 1983). Briggs and Shantz (1913) and Shantz and Piemeisel (1927) evaluated many crop and weed species under the environmental conditions of the Central Great Plains, and found that proso millet produced the lowest transpiration ratio (unit of water transpired per unit of total dry matter produced) of all the species surveyed, indicating that this crop exhibits efficient water use behavior. This may be attributed in part to the $C_4$ photosynthetic mechanism (Martin et al., 1976) of proso millet. Greb (1979) suggested that the low straw/grain ratio of proso millet also contributes to its adaptation to the semiarid Central Great Plains region.

The major crop rotation under nonirrigated conditions in the Central Great Plains is winter wheat-summer fallow-winter wheat (Hinze and Smika, 1983). This rotation consists of a winter wheat planting in early to late September followed by harvest of the crop in early to late July of the following year. The land is then left noncropped or summer fallowed, under weed-free conditions, for a period of approximately 56 wk to store fallow-period precipitation. The same area of land is then replanted to wheat again in September. The precipitation stored during the fallow or noncropped period is needed in most years to produce a successful wheat crop (Greb, 1983). This means, however, that a wheat crop is produced on the same land area in only 1 of every 2 yr.

Traditionally, proso millet has been grown in this area as an alternate crop where winter wheat may have failed prior to 1 June or when allotment programs have restricted winter wheat acreages. There has been, however, little research conducted to establish the appropriate crop rotations and management schemes for optimum grain production of proso millet in this area.

With the development of more efficient cultural practices for storing soil water during fallow periods (Anderson et al., 1986), introduction of new crop rotations to this area should become more feasible. For example, in the eastern region of the Central Great Plains, where precipitation levels are slightly higher, winter wheat-grain sorghum [*Sorghum bicolor* (L.) Moench]-fallow and winter wheat-corn (*Zea mays* L.) -fallow rotations have proved successful (Hinze and Smika, 1983). Similar rotations or substitution of proso millet for other crops into a rotation might prove to be successful for this region. This would allow the production of two crops in 3 yr instead of the normal production of one crop in 2 yr.

The objective of this study was to determine the effect of three crop rotations involving proso millet on soil water storage, proso millet production, and water use.

## MATERIALS AND METHODS

This study was conducted over five growing seasons (1973–1977) at the Central Great Plains Research Station located near Akron, CO. Although the plot areas in successive years of the study were not located on the same area of the station, the soil type for each site was a Rago silt loam soil (fine, montmorillonitic, mesic Pachic Argiustolls) with an approximate organic matter content of 13 g/kg and a pH of 7.4

Treatments consisted of a factorial combination of three crop rotation sequences and three proso millet cultivars. The crop rotations were: (i) millet-millet (M-M), (ii) winter wheat-millet (W-M), and (iii) fallow-millet (F-M); and the three proso millet cultivars were: 'Common White', 'Leonard', and "Turghai'. The cultivars represent a range in phenotypic variation in maturity and height. Leonard is a tall-stature, late-maturing cultivar, and Common White and Turghai are short-stature, medium-maturing cultivars. The experimental design each year was a randomized complete block replicated four times in a split-plot arrangement, with crop rotation sequences as main plots and cultivars as split plots. Main plot dimensions were 7.6 by 24.4 m and split plot dimensions were 2.5 by 24.4 m.

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Table 1. Climatological data summarized over five cropping seasons at Akron, CO.

| Climatological variables† | Crop season 1973 | 1974 | 1975 | 1976 | 1977 | 5-yr $\bar{x}$ | 73-yr $\bar{x}$ |
|---|---|---|---|---|---|---|---|
| Precipitation, m | 163 | 151 | 233 | 149 | 114 | 162 | 180 |
| Open pan evaporation, mm‡ | 975 | 999 | 927 | 1038 | 934 | 974 | 887 |
| Mean daily temperature, °C | 21.3 | 21.5 | 21.1 | 21.5 | 22.4 | 21.6 | 21.5 |

† All climatological parameters were recorded from the date of planting through maturity. ‡ Class A open pan evaporation.

The intent of using the three rotation treatments was to determine how the length of the noncropped period of each rotation affected soil water storage and proso millet productivity and water use. Therefore, only the productivity of the second component (proso millet) of the rotation was measured. The M-M, W-M, and F-M rotations for the beginning year (1977) of the study were initiated by harvesting proso millet, winter wheat, and proso millet on 15 Sept. 1976, 18 July 1976, and 18 Sept. 1975, respectively. The proso millet crop to be evaluated in 1977 was then planted on 2 June and harvested on 14 Sept. 1977. Thus, the noncropped period preceding the millet planting in each of the rotations was approximately 34, 42, and 86 wk, respectively. The F-M rotation included an entire summer season (April–October) in which the land was fallowed or no crop was grown. The rotations in the remaining years of the study were established in a similar manner on different sites at the research station. Subsurface tillage with a V-sweep blade controlled weeds during the noncropped period of each crop sequence.

A seeder with a double-disk type opener (0.25-m row spacing) was used to seed the plots at a seeding rate of 11.2 kg/ha. The crop was fertilized prior to planting according to soil test recommendations so that plant nutrients would not limit productivity. After the first year of the study, weed control in the proso millet crop was maintained with a preplant application of atrazine (2-chloro-4-ethylamino-6-isopropylamino-S-triazine) at the rate of 1.12 kg/ha of active ingredient.

Table 2. Noncrop period precipitation, preplant soil water, postharvest soil water, and seasonal evapotranspiration (ET) for the three crop rotations over five cropping seasons at Akron, CO.

| Crop rotation† | Crop season 1973 | 1974 | 1975 | 1976 | 1977 | $\bar{x}$ | CV, %‡ |
|---|---|---|---|---|---|---|---|
| | | | Noncrop period precipitation, mm | | | | |
| M-M | 373 | 223 | 249 | 185 | 261 | 258 | 27 |
| W-M | 480 | 257 | 321 | 251 | 310 | 324 | 29 |
| F-M | 708 | 714 | 623 | 592 | 530 | 633 | 12 |
| | | | Preplant soil water, mm | | | | |
| M-M | 268 | 126 | 128 | 92 | 136 | 150 | 45 |
| W-M | 285 | 136 | 156 | 155 | 154 | 177 | 34 |
| F-M | 244 | 209 | 179 | 189 | 204 | 205 | 12 |
| LSD (0.05) | NS | 29 | 31 | 37 | 28 | 13 | – |
| | | | Postharvest soil water, mm | | | | |
| M-M | 59 | 47 | 50 | 36 | 48 | 48 | 17 |
| W-M | 85 | 46 | 61 | 32 | 58 | 56 | 35 |
| F-M | 41 | 57 | 65 | 49 | 56 | 54 | 17 |
| LSD (0.05) | 27 | NS | NS | NS | NS | NS | – |
| | | | Seasonal ET, mm | | | | |
| M-M | 372 | 230 | 311 | 205 | 202 | 264 | 28 |
| W-M | 363 | 241 | 328 | 272 | 210 | 283 | 22 |
| F-M | 366 | 303 | 347 | 289 | 262 | 313 | 14 |
| LSD (0.05) | NS | 23 | NS | 18 | 19 | 12 | – |

† The M-M, W-M, and F-M designations refer to millet-millet, winter wheat-mittet, and fallow-millet rotations, respectively.
‡ CV refers to coefficients of variation, which was calculated using treatment means within each crop rotation.

Total seasonal evapotranspiration (ET) for the various treatments was determined by the water balance method (Hillel, 1982), using preplant soil water, postharvest soil water, and growing season precipitation. Soil water content was determined for each treatment combination prior to planting and after grain harvest using the gravimetric method. Samples were taken in 0.3-m increments to a depth of 1.8 m, with two samples per plot per sampling date. The assumption was made that if runoff or drainage (below 1.8 m of soil profile) of water occurred, it occurred to the same extent over the whole experimental plot area. Precipitation received during the millet growing season and noncropped period of each crop sequence was recorded.

Plant samples were harvested at maturity from four rows, 1.2 m long, to determine grain and total dry matter yields. The grain was then threshed from the harvested samples. Grain and vegetative samples were oven-dried at 65°C for 48 h to determine water content. Grain yield (GY) and total dry matter yield (TDMY) were reported on a 0% water basis. Harvest index (HI) was determined by dividing GY by TDMY and multiplying by 100.

Analysis of variance (ANOVA) was used to determine differences and interactions among treatment variables. The coefficient of variation (CV) was used to measure variability of treatment means within crop rotations and cultivars and across years. This form of statistical analysis provided an indication of the stability of average crop yields for the crop rotation and cultivar treatments across years in the study. Linear regression analysis was used to determine the response of GY and TDMY to total seasonal water use.

## RESULTS AND DISCUSSION

The environmental data for the five growing seasons during which this study was conducted are presented in Table 1. The average climatological conditions during the duration of this study were slightly warmer and drier than the long-term average, although there was some variation across the years of the study.

The amount of precipitation available for soil water storage during the noncropped period varied significantly across years and crop rotations (Table 2). On the average, the W-M and F-M rotations received 26 and 145% more precipitation, respectively, than the M-M rotation. This difference in precipitation was associated with the length of the noncropped period for the three crop rotations, with the period being 34, 42, and 86 wk for the M-M, W-M, and F-M rotations, respectively. The variability of the precipitation received was significantly less for the F-M rotation than for either the M-M or W-M rotations, as indicated by the CVs for the respective rotations.

The amount of available preplant soil water differed among the three crop rotations in 4 of the 5 yr of the study (Table 2). The average amount of preplant soil water in the W-M and F-M sequences was 18 and 37% higher, respectively, than that of the M-M rotation.

The variability of preplant soil water for each crop rotation decreased in proceeding from the M-M to the F-M rotation, as indicated by the CVs for the three crop sequences. The difference in preplant soil water among the crop rotations was associated with the amount of precipitation received during the noncropped period of each rotation. It would appear, however, that the precipitation received was not stored with equal efficiency among the three crop rotations. For example, the F-M rotation received 145% more precipitation than the M-M sequence, yet the F-M sequence stored only 37% more soil water than the M-M rotation. Thus, the F-M rotation was very inefficient in storing available precipitation as soil water. The inefficiency in soil water storage associated with the F-M sequence was probably due to the long noncropped period, which involved warm summer months when evaporation rates would tend to be high, whereas the noncropped period of the M-M and W-M rotations would not involve as many summer months, and, therefore, precipitation storage would probably be more efficient (Greb, 1983; Unger, 1983).

The level of available water remaining in the soil profile at harvest did not differ among cultivars for the first 2 yr of the study (data not shown). Therefore, in subsequent years, soil water at harvest was determined for only one cultivar (Common White) within each crop rotation to reduce the number of soil water gravimetric determinations. Consequently, the data do not reflect differences in ET among cultivars and are reported for the different crop rotation systems only (Table 2). There were no differences in the amount of soil water remaining in the profile at maturity for the three crop rotations in all years of the study, with the exception of 1973. Therefore, differences in total seasonal ET between crop rotations were mainly associated with variation in the preplant soil water storage, leading to differences in crop water use (Table 2). There were significant differences in seasonal ET among the three crop rotations in 3 of the 5 yr of the study, with the W-M and F-M sequences showing a 7 and 19% higher ET, respectively, than the M-M sequence for the 5-yr average.

The values for TDMY, GY, and HI are given in Tables 3, 4, and 5, respectively. There was no crop rotation × cultivar interaction for TDMY, GY, or HI in any of the years of the study. Thus, the data have been presented as averages for crop rotation and cultivars. A crop rotation × year interaction was observed for both TDMY and GY. This interaction was associated with very low TDMY and GY values for the M-M rotation relative to the other two rotations in 1973. The low relative yield of the M-M sequence was due to a weed infestation, which competed severely with the crop.

There were differences among crop rotations for TDMY, GY, and HI in 5, 4, and 3 of the 5 yr, respectively (Tables 3, 4, and 5). The W-M and F-M sequences produced, on the average, 37 and 76% more TDMY and 50 and 116% more GY, respectively, than the M-M sequence. Additionally, variability across years and within rotations decreased in proceeding from the M-M to F-M rotation for TDMY, GY, and HI.

While there was a significant cultivar × year interaction for the TDMY, GY, and HI variables, the ranking of the cultivars across years for these variables did not deviate significantly across years. Thus, the 5-yr averages would appear to provide a representative description of the performance of the cultivars across years. In general, the cultivar Leonard produced more TDMY and less GY and had a lower HI than either Common White or Turghai, with little difference ex-

**Table 3. Total dry matter yield of three proso millet cultivars grown under three crop rotations over five cropping seasons at Akron, CO.**

| Crop rotation† | Cultivar | 1973 | 1974 | 1975 | 1976 | 1977 | $\bar{x}$ | CV,‡ |
|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | | % |
| M-M | | 2399 | 3365 | 5348 | 2204 | 2367 | 3137 | 42 |
| W-M | | 5800 | 4172 | 5159 | 3872 | 2498 | 4300 | 30 |
| F-M | | 5966 | 5848 | 6238 | 5479 | 4107 | 5528 | 15 |
| LSD (0.05) | | 1657 | 1438 | 832 | 754 | 381 | 416 | – |
| | Common White | 4719 | 3970 | 5380 | 4028 | 3052 | 4230 | 21 |
| | Leonard | 4948 | 5354 | 6582 | 3814 | 3028 | 4745 | 29 |
| | Turghai | 4655 | 4062 | 4784 | 3713 | 2892 | 4021 | 19 |
| | LSD (0.05) | NS | 668 | 592 | NS | NS | 226 | – |

† The M-M, W-M, and F-M designations refer to millet-millet, winter wheat-millet, and fallow-millet rotations, respectively.
‡ CV refers to coefficient of variation, which was calculated using treatment means within each crop rotation.

**Table 4. Grain yields of three proso millet cultivars grown under three crop rotations over five cropping seasons at Akron, CO.**

| Crop rotation† | Cultivar | 1973 | 1974 | 1975 | 1976 | 1977 | $\bar{x}$ | CV,‡ |
|---|---|---|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | | | | % |
| M-M | | 924 | 1034 | 2225 | 717 | 776 | 1135 | 55 |
| W-M | | 2597 | 1469 | 2188 | 1404 | 840 | 1700 | 41 |
| F-M | | 2438 | 2529 | 2958 | 2481 | 1861 | 2454 | 16 |
| LSD (0.05) | | 813 | 485 | NS | 442 | 196 | 342 | – |
| | Common White | 2255 | 1863 | 2612 | 1583 | 1137 | 1890 | 30 |
| | Leonard | 1800 | 1350 | 2395 | 1464 | 1103 | 1622 | 31 |
| | Turghai | 1904 | 1820 | 2365 | 1555 | 1238 | 1777 | 24 |
| | LSD (0.05) | 214 | 270 | NS | NS | NS | 188 | – |

† The M-M, W-M, and F-M designations refer to millet-millet, winter wheat-millet, and fallow-millet rotations, respectively.
‡ CV refers to coefficient of variation, which was calculated using treatment means within each crop rotation.

**Table 5. Harvest index of three proso millet cultivars grown under three crop rotations over five cropping seasons at Akron, CO.**

| Crop rotation† | Cultivar | 1973 | 1974 | 1975 | 1976 | 1977 | $\bar{x}$ | CV,‡ |
|---|---|---|---|---|---|---|---|---|
| | | % | | | | | | |
| M-M | | 38.5 | 30.7 | 41.6 | 32.5 | 32.8 | 35.2 | 13 |
| W-M | | 35.1 | 35.2 | 42.4 | 36.3 | 33.6 | 36.5 | 9 |
| F-M | | 40.9 | 43.3 | 47.4 | 45.3 | 45.3 | 44.4 | 6 |
| LSD (0.05) | | NS | 9.1 | NS | 7.1 | 2.5 | 2.6 | – |
| | Common White | 47.8 | 46.9 | 48.6 | 39.3 | 37.3 | 44.7 | 12 |
| | Leonard | 36.4 | 25.2 | 36.4 | 38.4 | 36.4 | 34.2 | 16 |
| | Turghai | 40.9 | 44.8 | 49.4 | 41.9 | 42.8 | 44.2 | 8 |
| | LSD (0.05) | 3.9 | 4.0 | 2.5 | NS | NS | 2.2 | – |

† The M-M, W-M, and F-M designations refer to millet-millet, winter wheat-millet, and fallow-millet rotations, respectively.
‡ CV refers to coefficient of variation, which was calculated using treatment means within each crop rotation.

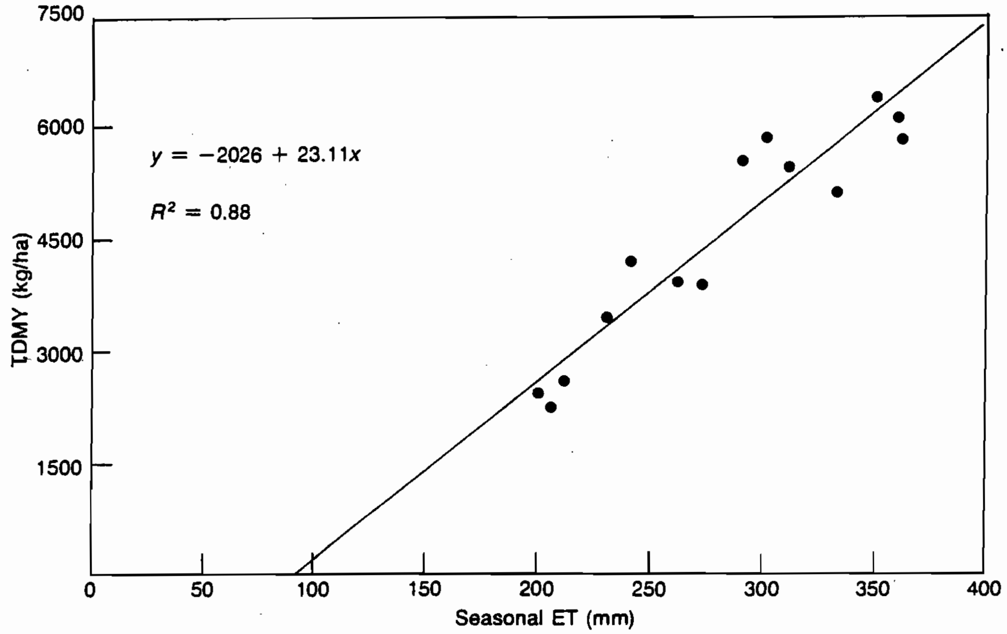


**Fig. 1. Total dry matter yield (TDMY) versus seasonal evapotranspiration (ET) for three proso millet crop rotations grown over five cropping seasons at Akron, CO.**

isting between the latter two cultivars for these variables. Furthermore, Common White and Turghai had smaller CVs than Leonard for TDMY, GY, and HI, indicating greater stability for these traits associated with the former cultivars versus the latter cultivar.

Considerable research has shown that seasonal ET and biomass yield are linearly related under water-limiting conditions in a number of crops (Hanks et al., 1969; Stewart et al., 1977; Hanks, 1983). Using the crop rotation × year treatment means for TDMY and the respective water use data, TDMY was found to be linearly related to seasonal ET (Fig. 1). Therefore, the variation in TDMY among crop rotations and years was largely related to variation in water use among cropping systems and years.

Although the cultivars displayed different trends for response of TDMY to ET, the slope and *y*-intercept values were not significantly different among the three cultivars (data not shown). Therefore, no difference in water use efficiency among the three cultivars used in this study was apparent for total biomass production. Tanner and Sinclair (1983) have indicated that the scope for improving water use efficiency of total dry matter production under nonirrigated conditions may be limited within crop species, noting that the major differences exist between crop species of different photosynthetic metabolic classes ($C_3$ vs. $C_4$). Passioura (1983) had proposed that manipulation of the HI rather than changes in water use efficiency of biomass production would have a greater effect on grain yields under water-limited conditions. The data of this study tend to support this hypothesis, since there was a positive correlation of 0.575 ($P \leq 0.05$) between GY and HI using the cultivar × year treatment means ($n$= 15). Austin et al. (1980) have also concluded that gains in productivity with genetic improvement in winter wheat were associated with increases in HI.

Grain yield and seasonal ET were also linearly related, with a high degree of association (Fig. 2). Thus, the differences in GY among the crop rotations and years were mainly due to differences in water use. This was somewhat unexpected, since total water use is not generally found to be as highly associated with GY as with TDMY. It has generally been suggested that timing of water supply has a more significant effect on GY than total water supply in other grain crops (Shaw, 1977; Passioura, 1983).

Another important parameter to be gained from Fig. 2 is the solution of the regression equation for the $x$ variable when the $y$ variable is set equal to zero, which was determined to be 132 mm. This value represents the point where the regression line crosses the $x$ axis and indicates the average amount of water required by the proso millet crop to initiate grain production in this environment. Smika and Whitfield (1966) reported a value of 160 mm for the initiation of grain production in winter wheat under Central Great Plains conditions, and Willis (1983) suggested that a range of 180 to 250 mm of water use was required by wheat to initiate grain production. Thus, it would appear that proso millet is more effective than winter wheat at utilizing water to produce grain.

Many aspects must be considered when adopting the appropriate cropping system for a given area. In this region, water must be considered as the most limiting factor for crop productivity (Greb, 1983). As water becomes limiting, the risk associated with crop production increases (Loomis, 1983). The level of risk tolerable to the producer will depend on many economic factors. The nonirrigating producer, however, will generally choose the cropping alternatives that minimize risk, assuming all other factors are equal (Loomis, 1983). These considerations make the introduction of proso millet into a cropping sequence a viable choice for crop production in the Central Great Plains because of its low water requirements.

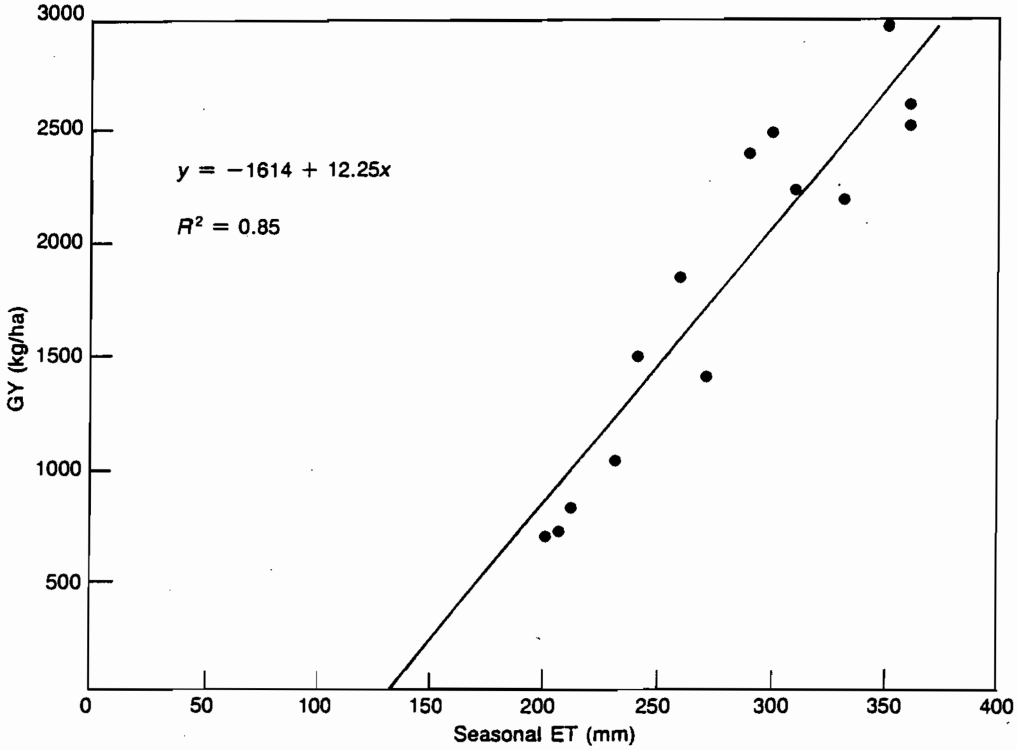


**Fig. 2. Grain yield (GY) versus seasonal evapotranspiration (ET) for three proso millet crop rotations grown over five cropping seasons at Akron, CO.**

The M-M rotation would not appear to be successful for proso millet production in this area, because yields for this sequence were the lowest and most variable of all the cropping systems tested (Table 4). Although the F-M sequence would initially seem to be a productive crop rotation, this sequence would produce a crop only 1 yr in 2. Therefore, if the long-term yields for this sequence were converted to an annual production basis (1227 kg/ha), they would be only slightly higher than the yields for the M-M sequence (1135 kg/ha). Additionally, the long noncropped period (86 wk) of the F-M rotation would be very inefficient in soil water storage (Greb, 1983; Unger, 1983). Furthermore, an extended noncropped period, such as the one associated with the F-M rotation, has the potential of predisposing the soil to increased erosion hazards, accelerated losses of organic C, a loss of soil structure, and accelerated salinization problems (de Jong and Steppuhn, 1983). Consequently, the W-M rotation would appear to be the most viable for proso millet production in this area. The additional 8 wk of noncropped period associated with the W-M sequence versus the M-M rotation increased water use by an average of 7% over the M-M sequence (Table 2), which increased grain yield by an average of 50% over the M-M rotation (Table 4). Moreover, the W-M sequence also reduced yield variability over the M-M sequence, thereby reducing the level of risk connected with this sequence. An added benefit of the W-M versus the M-M rotation could be the interruption of insect and disease cycles associated with monoculture cropping (Martin et al., 1976). It is likely that the W-M rotation would be even more successful in this region if reduced tillage systems were used to maximize soil water storage during the noncropped period of the rotation (Anderson et al., 1986).

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# Growth and Composition of Grain Sorghum with Limited Nitrogen

**H. R. Lafitte and R. S. Loomis***

## ABSTRACT

**A study of N fertilization of grain sorghum [*Sorghum bicolor* (L.) Moench] was conducted in two fields on a Typic Xerorthent with contrasting patterns of N availability, to extend our understanding of how the partitioning of N to vegetative parts and to structural biomass influences grain yield and N-use efficiency. The study was supported by detailed analyses of N and dry matter distribution, and proximal analyses of biochemical composition. Nitrogen accumulation differed greatly, but the patterns of N partitioning and the structural carbohydrate content of vegetative parts at equivalent developmental stages were little affected. Changes in dry weight partitioning among vegetative parts were primarily a result of the parts' differential abilities to store nonstructural compounds. In contrast, the structural carbohydrate content of panicles was affected by N availability. Low N supply resulted in leaves with a smaller N content, and lower light conversion efficiency was observed. In addition, those canopies were not able to supply as much N to panicle growth. Roughly two-thirds of the observed effects of N deficiency on grain yield were due to structural limitations to growth; the remaining effects were associated with reduced conversion efficiency per unit leaf area.**

***Additional Index Words:* *Sorghum bicolor* (L.) Moench, Nitrogen utilization efficiency, Nitrogen mobilization, Light utilization efficiency.**

NITROGEN supply limits crop productivity directly and indirectly. Growth, in particular the formation of new cells, is affected directly by shortages of nitrogenous compounds for "structural" roles, as enzymes and as constituents of walls and membranes. Indirect effects follow, for example, through less leaf area resulting in less light interception and modified metabolic rates. While the influence of N limitation on photosynthetic rates has received considerable attention, information about direct or structural restrictions of growth is fragmentary. When the production of new plant material is limited by a structural requirement for protein, increases in biomass yield per unit of protein may be limited to low-N materials such as structural and nonstructural carbohydrates that can be added to existing cells. An examination of the relationship between the partitioning patterns of N and dry weight under conditions of N limitation may lead to a clearer understanding of the relative importance of the factors affecting yield. The study reported here employed grain sorghum because of its ability to accumulate very large amounts of dry weight per unit N.

It is well established that N limitation changes dry weight partitioning patterns in sorghum (Roy and Wright, 1973). Several studies indicate that a threshold N concentration is required for leaf expansion (Lugg and Sinclair, 1981; Muchow, 1988a), and that this threshold may be greater for leaf tissues than for other tissue types (Wilson and Brown, 1983). It has also been observed that reproductive (grain) yield is frequently more strongly affected by N stress than is biomass yield (Maranville et al., 1980). Changes in the partitioning of carbon among plant parts with N stress may be a result of a differential sensitivity of growth to N concentration among tissue types. Such differences in partitioning could also reflect the capacity of each tissue type to accumulate compounds that do not contain N.

The primary objective of this study was to quantify the structural limitations to yield in grain sorghum with a low N supply. Grain sorghum is often sown in N-deficient soils, and an understanding of the nature of whole-plant N responses in this crop is central to the development of improved cultivars for such environments. A secondary objective was to examine the chemical basis of changes in dry weight partitioning patterns that result from structural limitations to growth under low N.

## MATERIALS AND METHODS

Two hybrid cultivars of grain sorghum (Asgrow 'Corral' and Ferry-Morse 'GT-350') were grown in the field at Davis, CA, during 1982 and 1983. The soil was a Yolo loam (mixed, thermic Typic Xerorthent) (Andrews, 1972) having good drainage properties. The field used in 1982 had been planted with *Triticum vulgare* L. the previous winter, while the 1983 field had supported *Phaseolus vulgaris* L. the previous summer and had been fallow during the intervening winter. Rows

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