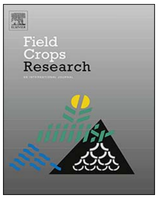
Field Crops Research 212 (2017) 34–44

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr



Water use and environmental parameters influence proso millet yield

David C. Nielsen*, Merle F. Vigil

USDA-ARS, Central Great Plains Research Station, Akron, CO 80720, United States

ARTICLE INFO

Keywords:
Proso millet
Water use
Yield
Wind
Temperature
Precipitation
Soil water

ABSTRACT

Proso millet (*Panicum miliaceum* L.) is a short-season, drought-tolerant C4 species capable of making use of limited available water supplies and is suitable for dryland crop rotations in the Central Great Plains. Previously published water use/yield production functions for proso millet have slopes lower than reported for other C4 species in this region. The objectives of this experiment were to determine the water-limited yield relationship for proso millet and to identify environmental factors that cause yields to be lower than predicted by the water-limited yield relationship. Water use and yield data were obtained from a long-term crop rotation experiment conducted under dryland conditions in northeast Colorado from 1995 to 2016. Stepwise linear regression analysis was used to determine important environmental factors influencing yield. The water-limited yield relationship had a slope consistent with other C4 species in this region (32.57 kg ha^{-1} per mm of water use). A relationship based on growing season water use, plant available soil water at planting, precipitation received from 12 to 18 August, number days in July and August with maximum temperature greater than 36˚C, daily average wind run and maximum wind gust during the week before swathing explained 88% of yield variability. The results of this analysis suggest that closing the yield gap for proso millet production could likely result from efforts to breed for enhanced shattering resistance and heat tolerance and from production methods that improve precipitation storage efficiency during the non-crop period prior to millet planting and increase available soil water at millet planting.

1. Introduction

Proso millet is a warm season grass ideally suited to dryland production in the semi-arid Central Great Plains of the United States due to its low water requirement, short growing season (60–90 days), and highly efficient C4 photosynthetic pathway (Lyon et al., 2008; Baltensperger, 1996; Shantz and Piemeisel, 1927). It is used for birdseed and livestock feed within the United States and for human consumption in other countries (Lyon et al., 2008). Production is mainly concentrated in the Great Plains states of Colorado, Nebraska, and South Dakota (Lyon et al., 2008). It is considered a good rotation crop to use following sunflower (*Helianthus annuus* L.) or corn (*Zea mays* L.) and prior to winter wheat (*Triticum aestivum* L.) because of its short growing season, shallow rooting depth (120 cm), and low water use (Lyon et al., 2008). The short growing season allows farmers to harvest the millet crop in time to plant winter wheat a few weeks later. This is important because in the Central Great Plains winter wheat serves as the base crop upon which most dryland crop rotations are based. Saseendran et al. (2010) used cropping systems simulation modeling to show that proso millet could be an important rotational crop to include with wheat and corn in semi-arid dryland cropping systems. Habiyaremye et al. (2017) provided a comprehensive review of proso millet history, growth, culture, production, uses, genetics, diseases, pests, and adaptability.

There are only a few previously published relationships of proso millet yield response to water use (Table 1). Those relationships have reported slopes ranging from 12.25 to 14.79 kg ha^{-1} per mm of water use. These slopes are far below what has been reported for other C4 crops in the Central Great Plains such as corn (25.7 kg ha^{-1} mm^{-1}, Nielsen et al., 2011) and grain sorghum (*Sorghum bicolor* L. Moench, 30.2 kg ha^{-1} mm^{-1}, Nielsen et al., 2017). Shantz and Piemeisel (1927) considered proso millet to be one of the most water use efficient crops of the 52 species that they collected data on, with a water requirement of 567 g water per g of seed produced. This water requirement converts to a yield response of 17.63 kg ha^{-1} per mm of water used. However, it should be noted that Shantz and Piemeisel (1927) only reported data for one year, and noted that there was wide year-to-year variation in the water requirement for other species for which they had collected

---

Abbreviations: WU, growing season water use (mm); PAW120, plant available water (mm) at proso millet planting in the 0–120 cm soil profile; P2, precipitation (mm) during the week of 12–18 August; Tmax36, number of days in July and August when maximum temperature was greater than 36 °C; Umax, maximum wind gust (km h^{-1}) recorded at 3 m during the week before swathing; WR, average wind run (km d^{-1}) recorded at 3 m during the week before swathing

* Corresponding author.

E-mail address: david.nielsen@ars.usda.gov (D.C. Nielsen).

http://dx.doi.org/10.1016/j.fcr.2017.06.025
Received 13 May 2017; Received in revised form 21 June 2017; Accepted 22 June 2017
0378-4290/ Published by Elsevier B.V.

Table 1
Previously reported slopes and offsets for water use/yield production functions[a] for proso millet.

Location	Slope kg ha^{-1} per mm	Offset mm	Years	Water Use Range mm	Source
Northeast Colorado	12.25	131	5	200–350	Shanahan et al. (1988)
Northeast Colorado	13.25	106	NA	NA	Lyon et al. (2008)
Northeast Colorado	14.79	163	1	185–270	Felter et al. (2006)

[a] Form of production function is yield [kg ha^{-1}] = slope X (water use [mm] − offset).

multi-year data. In addition to these previously reported water use-yield relationships for proso millet are the findings of Lyon et al. (1995) and Felter et al. (2006) who showed the strong influence of available soil water at planting on proso millet seed yield. Nelson and Fenster (1983) used stepwise multiple regression to determine that June rainfall was the most influential parameter affecting (positively) proso millet stand count and July rainfall was the most influential parameter affecting (positively) proso millet yield.

Several researchers have reported on the detrimental effects of water stress on proso millet yield for the period shortly before and after anthesis (Seghatoleslami et al., 2008; Emendack et al., 2011; Matsuura et al., 2012). Although there appear to be no reported field or greenhouse studies of the effects of high temperatures on proso millet yield, Habiyaremye et al. (2017) suggested that temperatures above 30 °C stopped proso millet vegetative growth and flowering. Additionally, lack of sufficient precipitation at planting or heavy rains following planting can both result in poor plant stands leading to greatly reduced millet yields (Lyon et al., 2008).

The previously reported responses of proso millet seed yield to growing season water use are much lower than would be expected for a C4 species. Hence, the objectives of this experiment were to: 1) define a water-limited yield relationship for proso millet for the central Great Plains region of the U.S. and 2) determine environmental factors that cause grain yield to fall below this water-limited yield relationship. The results should help to guide both plant breeders and agronomic managers in determining plant characteristics and management practices that maintain yield potential under the varying environmental conditions of the Central Great Plains.

2. Materials and methods

Proso millet water use and yield data were collected from 1995 to 2016 as part of an ongoing long-term alternative crop rotation experiment conducted at the USDA-ARS Central Great Plains Research Station (40°09′ N, 103°09′ W, 1383 m elevation above sea level) located 6.4 km east of Akron, CO. The soil was a Weld silt loam (Aridic Argiustolls) (https://soilseries.sc.egov.usda.gov/OSD_Docs/W/WELD.html, accessed 19 April 2017). The long-term experiment was established in the fall of 1990 and has been previously described by Anderson et al. (1999), Bowman and Halvorson (1997), and Nielsen and Vigil (2010). Proso millet was grown in 18 different crop rotations (2-yr, 3-yr, 4-yr, opportunity cropping). Variation in available soil water at planting and millet water use in a given year occurred because of differences in water use by the various preceding crops, which were wheat, corn, sunflower, safflower (*Carthamus tinctorius* L.), or pea (*Pisum sativa* L.). Each phase of each rotation appeared every year. Individual plot size was 9.1 by 30.5 m with east-west row direction. Each year of the study had three replications of each rotation.

All rotations were managed under no tillage management with weed control during both cropped and non-crop periods consisting of contact and residual herbicide applications applied at recommended rates. Herbicides used in the rotations were glyphosate (*N*-phosphonomethyl)glycine); paraquat (1,1′-dimethyl-4,4′-bipyridinium dichloride); atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine); 2,4-D (2,4-dichlorophenoxyacetic acid); dicamba (3,6-dichloro-2-methoxybenzoic acid); fluroxypyr ([4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy] acetic acid); imazamox (2-[4,5-dihydro-4-methyl-4-(1-methyethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid); and carfentrazone (ethyl-alpha-2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-,2,4-triazol-1-yl]-4-fluorobenzenepropanoate).

Dates of millet planting, swathing, and harvest are given in Table 2. Row spacing was 0.19 m. Millet was planted at 16.8 kg ha^{-1}. Nitrogen and phosphorus were applied at planting at rates shown in Table 2. Harvest sample areas were approximately 28–35 m^2. Millet grain yield is reported at 120 g kg^{-1} moisture content.

Soil water was measured at two locations near the center of each plot at 0.3-m intervals with a neutron probe (Model 503 Hydroprobe, CPN International, Martinez, CA) via the installation of neutron probe access tubes in each plot. The depth intervals were 0.3–0.6 m, 0.6–0.9 m, 0.9–1.2 m, 1.2–1.5 m, and 1.5–1.8 m, with the neutron probe source centered on each interval. Volumetric soil water in the 0.0–0.3 m surface layer was determined using time-domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, CA) with 0.3-m waveguides installed vertically approximately 40 cm from the neutron probe measurement site to average the water content over the entire layer. The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Bulk density was determined from the dry weight of the soil cores (38 mm diameter by 300 mm length) taken from each depth at the time of neutron probe access tube installation.

Available soil water at planting was computed by subtracting the lower limit of water availability at each soil water measurement depth (Ritchie, 1981; Ratliff et al., 1983) from the calculated volumetric water at that depth and multiplying the difference by the soil layer thickness (0.3 m). The lower limit of water availability at each of the six measurement depth intervals (0.100, 0.129, 0.087, 0.067, 0.086, 0.119 m^3 m^{-3}, respectively, for the 0.0–0.3 m surface layer down to the 1.5–1.8 m lowest layer) was determined previously in the plot area as the lowest volumetric water value observed for each crop over a period of several years (Nielsen et al., 2011). The individual values of available water at each of the top four depths in each plot were summed to give the profile plant available soil water at each of the two measurement locations in each plot and those two values were averaged to give one value of available soil water for each plot.

Full season water use was calculated as the difference between soil water readings at planting and swathing plus growing season precipitation. Precipitation was manually measured daily at two locations in the plot area and averaged. Runoff and deep percolation were assumed to be negligible. This was considered a reasonable assumption as the slope in the plot area was < 1% and visual observations in the plot area following heavy rains did not show evidence of runoff. Also, analysis of the soil water changes over time at the three deepest measurement layers did not show any evidence of increasing soil water content that would indicate deep percolation. Other weather parameters that were measured at a site approximately 250 m from the experimental area were daily pan evaporation from a Class A evaporation pan, air temperature at a height of 1.5 m above an unirrigated grass surface, and daily average wind run and daily maximum wind gust at a height of 3.0 m above the grass surface.

Swathing of millet was performed when the top of the main head had mature seed, as recommended by Lyon et al. (2008) and Berglund (2007). Harvest with a grain combine equipped with a pickup head occurred an average of nine days after swathing (Table 2) during which time the grain dried in the windrow created with the swather. Swathing