Optimizing Water Use with High-Transpiration-Efficiency Plants

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Abstract
High transpiration efficiency (TE) is one way to optimize water use. Plants with high TE produce more biomass per unit of water consumed than those with low TE. One novel solution to preserve water in soil is to identify plants with high TE. High TE is especially important in semi-arid regions where water is scarce. Grain sorghum (*Sorghum bicolor* Moench) is widely grown in these regions. Studies comparing sorghum lines known to have high and low TE have not been done. We grew in a greenhouse eight lines of sorghum, four known to have high TE and four known to have low TE, in pots with a commercial potting mix under well-watered and dry conditions. Relative water content, stomatal resistance, and pressure potential of the leaves were measured. High TE plants emerged better than low TE plants, which suggested that high TE lines have faster root growth. Under both watering regimes, relative water content, stomatal resistance, and pressure potential of high TE lines were similar to those of low TE lines. Because above-ground water relations did not distinguish high and low TE lines, the results suggested that research needs to focus on roots to determine why the lines differ in TE.

Key Words
Dry regions, plant root, drought, water-use efficiency, transpiration ratio, C_4 plant

Introduction

Grain sorghum is one of the most important crops grown in dry areas. Even though sorghum is classified as a drought-resistant species, the major environmental factor limiting its range of adaptation is drought (Gaosegelwe and Kirkham 1990). Genotypes of sorghum that make efficient use of water are needed for growth under drought in semi-arid regions. Water-use efficiency is defined the production of dry matter per unit of water consumed in evapotranspiration (water lost from soil and plants). Transpiration efficiency is defined as the production of dry matter per unit of water consumed in transpiration. Water lost from soil is excluded in the calculation. The reciprocal of transpiration efficiency is transpiration ratio, which is the ratio of weight of water transpired by a plant during its growing season to the weight of dry matter produced (usually exclusive of roots) (Glickman 2000). Understanding efficient water use is one of the most challenging problems facing scientists today (Zea-Cabrera *et al.,* 2006).

Almost a century ago, Briggs and Shantz (1913) showed that crop species differ in their transpiration efficiency. Since then, the C_3 and C_4 photosynthetic pathways have been elucidated, and differences in transpiration efficiency have been related to them. Plants with the C_4 type of photosynthesis have transpiration efficiencies that are about twice those of C_3 plants (Turner, 1993). However, within each species, differences in transpiration efficiency occur, including the C_4 plant, sorghum (Hammer *et al.,* 1997; Mortlock and Hammer, 1999).

An intensive breeding program has been carried out by personnel of the United States Department of Agriculture to screen for transpiration efficiency in sorghum (Xin *et al.,* 2009). In this work, 341 lines of sorghum have been screened for transpiration efficiency under greenhouse conditions. From these studies, the eight lines used in the current work were chosen. Four of them have high transpiration efficiency and four of them have low transpiration efficiency. However, because the plant-water relations of sorghum lines known to have high transpiration efficiency or low transpiration efficiency have not been compared, we measured their relative water content, stomatal resistance, and pressure potential to determine if they differed between high-TE and low-TE lines.

Materials and methods

Details of the experimental procedure are given by Thevar (2008). Briefly, the experiment was carried out between 3 December 2006 and 16 February 2007 in a greenhouse at Kansas State University in Manhattan, KS (39^{o}08'N, 96^{o}37'W, 314 m above sea level). The four lines with low TE were: PI257309 (from Argentina; Guinea-bicolor race; Nigricans-bicolor working group; Pedigree Mf.G.F:1228), PI295121 (Australia; Caudatum race; breeding material working group; Pedigree CAPRICORN), PI586381 (Cameroons; Guinea-caudatum race; Sumac working group; Pedigree IS 27595), and PI267532 (India; Kafir-caudatum race; Caffrorum-bicolor working group; Pedigree IS 2879). The four lines with high TE were: PI567933 (Beijing, China; Bicolor race; Nervosum-Kaoliang working group; Pedigree ER HUANG JIN), PI391652 (Shaanxi, China; race unknown; breeding material working group; Pedigree T'so 1MS), PI533946 (India; Durra-bicolor race; Durra-dochna working group; Pedigree MS385AXIS1008SA6473PB3R), and PI584085 (Uganda; Caudatum race; Caudatum-niricans working group; Pedigree 94USE9327).

Plants grew under greenhouse conditions in pots with a commercial greenhouse mix. Six seeds of each line, germinated in a Petri plate, were planted in a pot. Pots were covered with plastic, following the procedure of Xin *et al.* (2008), to prevent soil evaporation. Plants grew through holes cut in the plastic. Emergence was recorded on Day 3 (3 days after germination began), 4, 5, 8, 12, and 16. On Day 16, each pot was thinned to three seedlings. Harvest was 16 February 2007 (Day 75). None of the plants had reached reproductive stage by harvest. There were two watering regimes: wet and dry. Water was added by placing a funnel inside the hole in the plastic where a plant emerged. After an initial drenching of the pots with a fertilizer solution, each wet-treatment pot received about 700 mL of water and each dry-treatment pot received about 300 mL water. Relative water content was determined three times during the experiment by using the method of Barrs and Weatherley (1962). Abaxial stomatal resistance was measured 10 times during the experiment with a steady state diffusion porometer (Model SC-1, Decagon Devices, Pullman, Washington, USA). Pressure potential was determined at harvest (Day 75) on the most recently matured leaf using a portable plant water status console (Model 3115, Soilmoisture Equipment Corp., Santa Barbara, California, USA). The experiment was a completely randomized block design with eight sorghum lines, two treatments (wet and dry), and three replications. Data for relative water content and stomatal resistance taken during the experiment were averaged together to get means and standard errors. Data for pressure potentials, determined once at harvest, are presented with standard deviations.

Results and discussion

Plants with high transpiration efficiency (TE) emerged better than plants with low transpiration efficiency. By Day 16, an average of four plants with high TE had emerged and an average of three plants with low TE had emerged. Even though six germinated seeds were planted in each pot, no pot had six seedlings emerge. More of the low TE plants than high TE plants died in the soil before they could emerge. More research needs to be done to determine the difference in early (pre-emergence) root growth of high and low TE plants.

Relative water content, stomatal resistance, and pressure potential of plants with high TE did not differ from that of plants with low TE (Table 1). Because of the large variability in measurements, measurements made on well-watered plants did not differ from those of drought-stressed plants. Well-watered plants tended to have higher relative water contents, lower stomatal resistances, and higher pressure potentials, but differences were not significant. The number of seeds available for experimentation precluded more replications, which might have reduced the variability. Also, the relatively poor emergence of the plants limited the number of measurements.

In sum, because there were no differences in the water-relations of the shoots of the high and low TE plants, the data suggested that the difference in TE may be related to root growth. The fact that the high TE plants emerged better than the low TE plants indicates that the roots of the high TE plants may grow faster and penetrate a soil profile more quickly than roots of low TE plants. This would allow high TE plants to get water at depth that low TE plants cannot take up. It also would allow them to grow more in early development, without a large loss of water by transpiration because leaves are still small. With less transpiration, TE would be increased. Because only limited studies of sorghum roots have been done under field conditions (Krieg 1983, p. 362), it is not known if greater root growth at the seedling stage would continue into later stages. However, a small advantage in early growth is compounded during the life cycle of a plant (Blackman 1919). So a sorghum line with a large root mass at the seedling stage would likely have a large root mass at maturity. With more roots, a line can take up more water for transpiration and photosynthesis. Transpiration and photosynthesis are directly related. When stomata are open, resulting in a high transpiration rate, more carbon dioxide can be taken up for photosynthesis. We plan to continue our pot studies with the lines differing in TE, as seeds of high TE and low TE plants become available. In these studies, we shall have more replications, so the high TE and low TE lines may show differences in relative water content, stomatal resistance, and pressure potential. Our future research also is going to focus on root growth under field conditions, where roots are not confined by pots. In these studies, we shall measure photosynthesis and transpiration. Preliminary work is already underway (Thevar, 2008). Our results reinforce the fact that one of the research challenges facing hydrology is the need for investigation not only of species-specific mechanisms of root water uptake (Rodríguez-Iturbe *et al.,* 2007) but also of line-specific mechanisms.

Table 1. Relative water content (g/g), stomatal resistance (s/cm), and pressure potential (MPa) of four lines of sorghum with low transpiration efficiency (TE) and four lines with high TE under well-watered or drought-stressed conditions. See text for details.

	Relative water content		Stomatal resistance		Pressure potential	
	Wet	Dry	Wet	Dry	Wet	Dry
Low TE						
PI257309	0.82±0.13	0.75±0.17	17.5±5.5	22.1±7.3	-1.72±0.35	-1.73±1.19
PI295121	0.83±0.11	0.92±0.04	24.1±28.0	11.3±3.1	-0.65†	-1.25†
PI586381	0.79±0.13	0.82±0.11	15.8±15.0	17.3±7.3	-2.55±0.07	-2.35±0.35
PI267532	0.83±0.13	0.71±0.19	21.1±12.0	18.6±15.6	-1.15±1.18	-2.23±1.52
High TE						
PI567933	0.84±0.06	0.78±0.16	26.1±13.4	32.5±24.1	-0.63±0.39	-2.22±0.55
PI391652	0.87±0.07	0.78±0.15	14.0±5.6	23.0±7.2	-1.73±0.74	-2.00±0.95
PI533946	0.90±0.06	0.79±0.11	23.7±12.7	23.2±9.8	-0.93±0.32	-2.30†
PI584085	0.79±0.20	0.77±0.17	19.0±12.1	25.0±23.2	-1.12±0.20	-1.90±0.35

†One value only

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References

Barrs HD, Weatherley PE (1962) A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Australian Journal of Biological Sciences* **15**, 413-428.

Blackman VH (1919) The compound interest law and plant growth. *Annals of Botany* **33**, 353-360.

Briggs LJ, Shantz HL (1913) The water requirement of plants. I. Investigations in the Great Plains in 1910 and 1911. United States Department of Agriculture, Bureau of Plant Industry, Bulletin No. 284, 49 pp.

Gaosegelwe PL, Kirkham MB (1990) Evaluation of wild, primitive, and adapted sorghums for drought resistance. In 'Challenges in Dryland Agriculture. A Global Perspective.' (Eds PW Unger, TV Sneed, WR Jordan, RW Jensen), pp. 224-226. (Texas Agricultural Experiment Station: College Station, Texas).

Glickman TS (Ed) (2000) 'Glossary of meteorology.' Second ed. (American Meteorological Society: Boston, Massachusetts), 855 pp.

Hammer GL, Farquhar GD, Broad I (1997) On the extent of genetic variation for transpiration efficiency in sorghum. *Australian Journal of Agricultural Research* **48**, 6349-655.

Krieg DR (1983) Sorghum. In 'Crop-Water Relations.' (Eds ID Teare and MM Peet), pp. 351-388. (John Wiley & Sons, New York).

Mortlock MY, Hammer GL (1999) Genotype and water limitation effects on transpiration efficiency in sorghum. *Journal of Crop Production* **2**, 265-286.

Rodríquez-Iturbe I, D'Odorico P, Laio F, Ridolfi L, Tamea S (2007) Challenges in humid land ecohydrology: Interactions of water table and unsaturated zone with climate, soil, and vegetation. *Water Resources Research* **43**, W09301, doi:10.1029/2007WR006073.

Thevar PA (2008) Transpiration efficiency of eight grain sorghum lines [*Sorghum bicolor* (L.) Moench]. M.S. Thesis (Kansas State University: Manhattan), 53 pp.

Turner NC (1993) Water use efficiency of crop plants: Potential for improvement. In 'International Crop Science I.' (Eds. DR Buxton, R Shibles, RA Forsberg, BL Blad, KH Asay, GM Paulsen, RF Wilson), pp. 75-82. (Crop Science Society of America: Madison, Wisconsin).
Xin Z, Franks C, Payton P, Burke JJ (2008) A simple method to determine transpiration efficiency in sorghum. *Field Crops Research* **107**, 180-183.
Xin Z, Aiken R, Burke J (2009) Genetic diversity of transpiration efficiency in sorghum. *Field Crops Research* **111**, 74-80.
Zea-Cabrera E, Iwasa Y, Levin S, Rodríguez-Iturbe I (2006) Tragedy of the commons in plant water use. *Water Resources Research* **42** (Supplement), W06D02, doi:10.1029/2005WR004514.