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Performance of soft red winter wheat subjected to field soil waterlogging: Grain yield and yield components

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ABSTRACT

Soil waterlogging impacts 25% of the global area planted to wheat and the development of waterlogging tolerant cultivars lags behind progress that has been made for other abiotic stresses. This study was conducted to identify sources of waterlogging tolerance in soft red winter wheat (SRWW) adapted to the southeastern United States, a region prone to yearly waterlogging. A set of 28 SRWW genotypes were evaluated over two growing seasons in field waterlogging experiments at the Rice Research and Extension Center in Stuttgart, Arkansas. Waterlogging at the late tillering stage resulted in a mean grain yield (GY) reduction of 34%, ranging from 16 to 49% within the tested lines. Total GY was impacted by lower kernel weight spike^{-1} resulting from reductions in kernels spike^{-1} and 1000 kernel weight, total biomass and to a lesser extent spike density. An interaction between genotype and the waterlogging treatment (GxT) was observed for days to heading, plant height, kernel weight spike^{-1}, kernels spike^{-1} and 1000 kernel weight with significant GxT detected for total GY during the first season only. Spectral reflectance measurements of normalized difference vegetative index were highly predictive of both GY ($R^2 = 0.77$) and total biomass ($R^2 = 0.64$) under waterlogging but not in the control, indicating potential for indirect high-throughput screening and selection. Overall, the genotypes 26R22, AR01167-3-1, Magnolia and USG 3555 had significantly higher GY than other genotypes under waterlogging, with USG 3555 also showing a non-significant GY reduction, indicating its potential as a genetic source of waterlogging tolerance.

1. Introduction

Soil waterlogging affects up to 10% of global land area, including 25% of the worldwide area planted to wheat (Powell et al., 2012). With global climate change predicted to result in increased winter precipitation, improving the waterlogging tolerance of wheat is a priority for plant breeders in growing regions prone to soil waterlogging such as the southeastern United States where soft red winter wheat (SRWW) is grown. During waterlogging stress, saturation of the air pore spaces in the soil results in hypoxia or anoxia due to very low or complete absence of oxygen available for the plant, respectively (Colmer and Voesenek, 2009). Low oxygen availability disturbs plant physiology and metabolism, resulting in reduced growth, delayed development and lower total grain yield (GY) and yield components (Dickin and Wright, 2008). A reduction in GY is physiologically explained by a lower number of molecules of adenosine triphosphate produced in the hypoxic environment, which triggers lactic acid and alcohol fermentation with fewer nutrients available for growth and development compared to aerobic conditions (Teakle et al., 2011).

Waterlogging stress duration and intensity, as well as the developmental stage at which the stress is applied, determine the extent of GY reduction. Rasaei et al. (2012) observed GY reductions of 11%, 26% and 45% for the winter wheat cultivar "Marvdasht" waterlogged for 10, 20 and 30 days, respectively, at the 4–5 leaf stage. Collaku and Harrison (2002), evaluated the effect of five weeks of

Abbreviations: GY, grain yield; Sm2, spikes m^{-2}; KNS, kernel number spike^{-1}; KWS, kernel weight spike^{-1}; TB, total biomass; HI, harvest index; TKW, 1000 kernel weight; DH, days to heading; pH, plant height; NDVI, normalized difference vegetative index.

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Table 1
Means and percentage of total variance attributed to genetic, treatment, genotype × treatment and other effects for grain yield and yield components in 28 wheat genotypes evaluated under control and waterlogging treatments at the RREC in Stuttgart Arkansas from 2012 to 2014.

Source	Yield ($g\,m^{-2}$)	Days to heading (days)	Plant Height (cm)	Test Weight ($kg\,hl^{-1}$)	Kernel wt. $spike^{-1}$ (g)	Kernels $spike^{-1}$	Spikes m^{-2}	Biomass ($g\,m^{-2}$)	Harvest index (%)	1000 kernel wt. (g)	NDVI
2012–2013											
Means											
Waterlogging	451	117	84	73	1.03	42	25	439	844	0.54	0.83
Control	263	121	79	70	0.74	37	20	347	505	0.51	0.78
% reduction	−42	3	−6	−3	−29	−13	−19	−21	−40	−5	5.8
Percent variance											
Treatment – TRT	59*	–	16*	9	57***	32***	37*	15	52*	5.0*	30***
Genotype – GEN	0	–	0	0	0	4**	0	0	0	4	2
Rep(TRT)	24***	–	9***	6.0***	7***	1	12***	31***	25***	0	28***
GEN × TRT	4**	–	22***	28***	12***	13	11**	12**	7***	14*	1
Residual	14	–	53	56	24	49	40	41	16	77	40
2013–2014											
Means											
Waterlogging	306	117	70	74	0.86	37	24	362	953	0.31	0.70
Control	265	118	63	71	0.63	31	20	426	926	0.28	0.67
% reduction	−13	1	−10	−3	−26	−14	−14	17	−3	−10	4.1
Percent variance											
Treatment – TRT	5	4	33*	7.0*	58***	47***	28***	4	0	25***	0***
Genotype – GEN	14**	44***	12***	12*	11**	35***	25***	14**	24***	11*	35***
Rep(TRT)	6**	4	15***	0	0	2***	1	3	13***	0	42***
GEN × TRT	0	0	0	1	5*	5***	4	0	0	5	0
Residual	76	48	40	81	26	12	43	80	64	58	23***

[a] Data taken on one replication in 2012–2013
* Indicates significance at P = 0.05
** Indicates significance at P = 0.01
*** Indicates significance at P = 0.001

uninterrupted waterlogging initiated at the tillering stage on 15 soft red winter wheat (SRWW) cultivars and reported an average GY reduction of 44%. Dickin and Wright (2008) observed GY reductions of 20 and 24% in winter wheat exposed to waterlogging for 44 and 58 days, respectively, beginning at the tillering stage. When treated at the same stage, a 32% reduction in GY was observed with 14 days of waterlogging in the Australian spring wheat cultivar ‘Wyalkatchem’, including a 50% reduction in tiller number (Robertson et al., 2009). Shao et al. (2013) reported GY reductions of 7.1–11.2% depending on the growth stage at the time of treatment, with the largest reductions observed at pre-anthesis. In addition to total GY, other studies have found reductions in yield components, including shoot weight (Khabaz-Saberi et al., 2006), spike density (Ali et al., 2012; Collaku and Harrison, 2002) and kernel weight (Ali et al., 2012; Collaku and Harrison, 2002; Musgrave and Ding, 1998) as well as root biomass (Araki et al., 2012).

Despite the economic impacts of soil waterlogging on wheat production, particularly in the winter wheat growing region of the southeastern U.S., reports on the performance of adapted genotypes is extremely limited. Collaku and Harrison (2002) reported GY reductions ranging from 15 to 60% in 15 SRWW cultivars grown under five weeks of continuous waterlogging stress, the only such study in SRWW. A follow-up study using F_2 derived families with the tolerant cultivar ‘Tchere’ as a parent reported kernel weight to have the highest heritability and that a 17% increase in GY could be achieved by a selection index incorporating GY, kernel weight and tiller number (Collaku and Harrison, 2005). Overall, the lack of information on the response of wheat genotypes to soil waterlogging stress is an obstacle toward determining genetic resources that could be integrated for developing cultivars with improved tolerance. Therefore the objective of this study was to evaluate the performance of 28 SRWW cultivars and breeding lines adapted to the southeastern U.S. in terms of their GY performance under field waterlogging stress. In addition, the contribution of yield components to total GY and the utility of normalized difference vegetative index (NDVI) as a tool to select high yielding genotypes was also explored.

2. Material and methods

2.1. Plant material and field experiments

A set of 28 SRWW cultivars and advanced breeding lines adapted to the southern U.S. growing region was used for this study. Field waterlogging experiments were carried out at the Rice Research and Extension Center (RREC) in Stuttgart, Arkansas in the 2012–2013 (YR1) and 2013–2014 (YR2) growing seasons. Stuttgart soils are characterized by a silt loam surface layer and a clay subsoil with low permeability (NRCS, 2013) and are prone to periodic waterlogging. The experimental design was a split plot with four replications in both years with the waterlogging treatment (waterlogging and non-waterlogging) as the main plot and genotypes as the subplots in a randomized complete block design (RCBD). Field plots consisted of seven rows drill seeded at a density of 280 plants m^{-2} with total plot area measuring 1.25 m wide × 6 m long. In addition to pre-plant application of P and K based on soil test recommendations, all plots were fertilized with 170 kg of N as urea in a split application, with 60% applied prior to the waterlogging treatment and 40% applied post waterlogging treatment.

Field waterlogging was performed similar to Collaku and Harrison (2002), by establishing 0.30 m high levees surrounding the experimental field and using water from a nearby reservoir to apply a flood application twice weekly to maintain soil saturation for the duration of the treatment. While not continuously monitored, periodic measurements of soil moisture content indicated that soil saturation was maintained throughout the experiment. In YR1, the waterlogging treatment was started on March 20, 2013 at Feekes stage 4 and terminated on April 17, 2013 at Feekes stage 5 (28 days). In YR2, the treatment was started on April 1 at Feekes stage 4 and terminated on April 14 at Feekes stage 5 (14 days). A shorter treatment time was used in the second year to lessen the stress impact and increase the observed genotypic variation for the measured traits not observed in the first year.