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Individual and combined effects of soil waterlogging and compaction on physiological characteristics of wheat in southwestern China

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A R T I C L E I N F O

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A B S T R A C T

The combined effects of soil waterlogging and compaction are important concerns in crop production. Two field experiments were performed over two seasons to examine the effects of soil waterlogging and high bulk density (BD) on the performance of winter wheat in terms of its agronomic and physiological traits. Trial 1 applied soil waterlogging at different stages (started at tillering, jointing, booting and anthesis). Trial 2 was conducted with soil waterlogging and compaction that created BD of the topsoil (1.6 g cm^{-3}).

Results: from trial 1 showed that the tillering stage was the most waterlogging-sensitive period. A 12% lower grain yield caused by waterlogging was primarily reflected in reductions in spike numbers. Waterlogging at jointing and booting stages reduced grain weight through decreased dry matter translocation.

Results: from the field trial 2 showed that soil compaction decreased grain yield by 4.8%, and waterlogging aggravated this reduction by 20.7% and 22.4% when fields were waterlogged for 2 weeks (WL_{2w}) and 4 weeks (WL_{4w}), respectively. A reduction in spike number from fewer tillers at stem elongation stage was the main reason for grain yield loss. Soil compaction combined with waterlogging duration did not affect root weight, but soil compaction reduced above ground biomass and root weight after the jointing stage. Furthermore, waterlogging accelerated leaf senescence, especially under compacted conditions, which significantly decreased photosynthetic capacity, resulting in a lower maximal PSII photochemical efficiency (F_v/F_m), apparent electron transport rate (ETR), effective quantum yield of photosystem II (ΦPSII) and photochemical quenching (qP). Root weight was positively related to the total above ground biomass; whereas the final grain yield was not linearly related to the shoot weight. SPAD value correlated positively with yield and PSII parameters (F_v/F_m, F_v/F_0). The study concluded that the tillering stage was most susceptible to waterlogging, and soil compaction combined with waterlogging at tillering stage had a larger harmful effect on root and shoot growth during or after waterlogging. SPAD readings may be a good surrogate for photosynthetic activity under waterlogging and compaction conditions.

1. Introduction

Waterlogging is a significant constraint on wheat (*Triticumaestivum*) production worldwide, particularly in the rice-wheat rotation regions of South and Southeast Asia, such as Bangladesh, Pakistan, India, Nepal and China (Samad et al., 2001; Wu et al., 2015). Waterlogging influences the survival, growth, and productivity of crops (Kozlowski, 1997; Jackson and Colmer, 2005), and has been reported to cause a reduction in root growth, photosynthesis (Glinski and Stepniewski, 1985), leaf area, and dry matter accumulation in wheat (Shao et al., 2013). Waterlogging adversely affects leaf expansion and formation and leads to premature leaf senescence and abscission, resulting in an inhibition of shoot growth (Kozlowski, 1997). Root growth, on the other hand, is reduced from the lack of oxygen available for root respiration and the presence of soil phytotoxins inhibiting root formation and promoting root decay (Pezeshki, 2001). However, yield is affected variably, depending on the crop's stage of development when the stress is applied (Mukhtar et al., 1990). Waterlogging usually occurs during the tillering phase of winter wheat in the Sichuan Basin when this area experiences saturated conditions from excessive rainfall, especially in autumn, when waterlogging often exceeds 4 weeks. At other times, there is a significant risk of intermittent waterlogging resulting from irregular and unseasonal rainfall. In either case, this generally results in poor establishment and weak growth of the crop.

In modern agriculture, frequent and untimely mechanized cultural operations on wet soil usually cause soil compaction, which adds to

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cropping constraints in the Sichuan Basin. The combined impact of soil compaction and waterlogging on crop physiology is key to understanding stress susceptibility mechanisms under field conditions. Generally, plant growth is restricted under severe soil compaction, and plants become even more vulnerable to stresses from dry conditions or too much rain. Additionally, soil compaction can cause changes in root system structure and retard soil penetration (Ripley et al., 2007; Chen and Weil, 2010; Grzesiak et al., 2016). Consequently, reduced root growth in compacted soil is caused by decreased oxygen availability and hypoxia is likely to limit root growth if there is < 10% air-filled pore space (Bengough et al., 2011; Grzesiak et al., 2016). Willatt (1986) observed that root length density in the upper 0.30 m of soil and rooting depth decreased as the number of tractor passes increased from zero to six. Similarly, crop growth in soil with high impedance to root growth causes changes in above ground biomass, through decreases in stem diameter, plant height, leaf number, area, thickness, and thickness of epidermal cells and cell walls (Clark et al., 2003; Fageria et al., 2006; Grzesiak et al., 2013). Growth reduction, decrease of stomatal conductance and photosynthesis and increased in membrane injury are the first responses to environmentally stressed plants (Ripley et al., 2007; Saliendra et al., 1996). Waterlogging reduces oxygen supply to the roots, which induces change in the intensity of dark respiration, an increase in the use of carbohydrates and the synthesis of antioxidants (Couee et al., 2006; Crawford, 2003; Sun et al., 2015). However, some researchers also reported that the effects of soil compaction are ameliorated by waterlogging (Saqib et al., 2004), but it does not alleviate the issue of waterlogging itself. According to Liu et al. (2015) optimizing subsoil bulk density would benefit crop production and the associated adverse soil water conditions, however, optimization of soil bulk density is an over simplification of the underlying issue of degraded soil structure.

China's Yangtze River basin is one of the most important regions for global rice-wheat rotation. Approximately 20 years ago, the mechanization level was very low in this area, so soil compaction did not impair wheat growth; winter wheat could be cropped in a wide area with large climatic and edaphic variation. As the level of agricultural mechanization increased, so to the necessity of timely and rapid tillage, this led to larger and heavier machinery. The more frequent and the random in-field use of this machinery have led to increased soil compaction. Especially during mechanized rice harvesting, when soil moisture content is very high, or even waterlogged, which results in further reductions in soil permeability, thus aggravating and perpetuating the incidence of waterlogged and degraded soil conditions. These conditions result in poor seedling establishment, growth and crop stress (Tullberg et al., 2007). In this paper, we applied waterlogging at different growth stages, and further described the effects of combined soil waterlogging and compaction on wheat growth, physiological characteristics and grain yield. Therefore, the purposes of this study were: (1) to identify the primary waterlogging-sensitive period of wheat in this area; (2) to examine the combined effects of soil waterlogging and compaction on wheat agronomic and physiological traits, and (3) to explain the relationship among grain yield and physiological traits under multi-environmental stresses.

2. Materials and methods

2.1. Experimental environment and management

Two field experiments were conducted in Guanghan County, Sichuan Province, China (30°99′ N 104°25′ E, 450 m asl) in two successive growing seasons: trial 1 in 2011/12 and 2012/13 and trial 2 in 2013/14 and 2014/15. Two popular wheat varieties (Neimai836 and Chuanmai104) were used in trial 1 and Chuanmai104 was used in trial 2. Neimai836 was bred by the Neijiang Academy of Agriculture Science and released in 2008; it is widely used in the hilly areas of southwestern Sichuan. Chuanmai104, a high yielding variety, was bred by the Crop Research Institute of Sichuan Academy of Agriculture Science and released in 2012.

The topsoil (0–20 cm) of the experimental field soil is a clay loam (29.7% sand, 28.8% silt, and 41.5% clay) with 43.84 g kg^{-1} of organic matter, 186 mg $kg^{-1}$of alkali-hydrolyzable N, 9.6 mg kg^{-1} of Olsen-P, and 113 mg $kg^{-1}$of exchangeable K; the surface 30 ~ 70 cm is sand clay with 55.8% sand, 20.0% silt, and 24.2% clay. Wheat was planted between 30 October and 3 November in plot areas of 13.68 m^2 (3.6 m wide × 3.8 m long) in 18 rows 0.2 m apart, which equated to a seeding rate of 250 seeds m^{-2}. N, P_2O_5 and K_2O were applied at 135 kg ha^{-1} as basal fertilizer to all the plots in the form of synthetic fertilizer (the contents of N, P and K were 15% each). Rust and powdery mildew were controlled by applying triadimefon (Chemical Industry Research and Design Institute of Sichuan Province) at the seedling stage (150 mL ha^{-1}) and with triadimefon (375 g ha^{-1}) and propiconazole (Jiangsu Fengdeng Pesticide Co. Ltd.; 75 mL ha^{-1}) at the jointing stage. Fusarium head blight and aphids were controlled with β-cypermethrin (45 g ha^{-1}) and acetamiprid (15 g ha^{-1}) (both produced by Sichuan Saiwei Biological Engineering Co. Ltd.) during grain filling.

2.2. Experimental design, sampling and measurement

2.2.1. Field trial1 (waterlogging at different crop stages)

The experiments were arranged using a split-plot design with three replicates, with the main plots as wheat varieties, while the waterlogging treatments were split plots. Fifty centimeter ridge spacing with 40 cm ridge height was built around each subplot, 50 cm depth ditches were excavated between the two subplots, and the two sides of ditches were covered by plastic film. Soil was then backfilled into the ditch to prevent the water movement between the plots. Four waterlogging (WL) treatments (WLt, WLj, WLb and WLa) were applied to evaluate its effects at Feekes' 2 (WLt, waterlogging at tillering), 4 (WLj, waterlogging at jointing), 9 (WLb, waterlogging at booting) and 10.5 (WLa, waterlogging at anthesis) after Large (1954) on physiological indicators, growth, and yield of wheat from 2011 to 2013, the control site was without waterlogging. All waterlogged treatments were conducted for 35 days, which was achieved by pumping water onto the plots 2 ~ 3 times per day to maintain a 1 ~ 2 cm layer of free water on the field surface in the daytime during the entire waterlogging period. At the end of each waterlogging treatment, the soil water content was monitored 2 ~ 3 times until the condition of control were recovered, so that the real period that the wheat was under waterlogging condition were 35 days of waterlogging treatments plus the days of soil water recovered similar to the control; thus, waterlogging period in WLt, WLj, WLb and WLa were 45, 42, 40 and 37 days, respectively.

At maturity, 3 plant rows (3.6 m × 0.6 m) in each plot were sampled for yield and yield components. The numbers of spikes were counted, and grain yield was adjusted to 13% moisture. All plants were oven dried at 70 °C to constant weight to determine their above ground dry biomass.

The number of days to anthesis was defined as the number of days from sowing to when half of the ears were flowering. Following anthesis, 100 plants with no pests or diseases were labelled. Samples of 10 ears were harvested from each plot from seven days after anthesis at five-day intervals until full maturity. The ears were oven-dried at 75 °C to constant weight, hand threshed, and the grain was then counted and weighed. The grain weight of these samples at each stage was used for non-linear regression analyses.

Leaf greenness of the topmost, fully expanded lamina, was measured in both cultivars during waterlogging at five-day intervals and at 0, 15, 25, and 35 days after anthesis, using a non-destructive, hand-held chlorophyll meter (SPAD-502; Konica Minolta Sensing Inc., Osaka, Japan). The SPAD readings were obtained from the one-third and two-third positions of each lamina. Ten laminae were measured in each subplot, and these values were averaged.