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Maize and soybean root front velocity and maximum depth in Iowa, USA

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ABSTRACT

Quantitative measurements of root traits can improve our understanding of how crops respond to soil and weather conditions, but such data are rare. Our objective was to quantify maximum root depth and root front velocity (RFV) for maize (*Zea mays*) and soybean (*Glycine max*) crops across a range of growing conditions in the Midwest USA. Two sets of root measurements were taken every 10–15 days: in the crop row (in-row) and between two crop rows (center-row) across six Iowa sites having different management practices such as planting dates and drainage systems, totaling 20 replicated experimental treatments. Temporal root data were best described by linear segmental functions. Maize RFV was 0.62 ± 0.2 cm d^{-1} until the 5th leaf stage when it increased to 3.12 ± 0.03 cm d^{-1} until maximum depth occurred at the 18th leaf stage (860 °Cd after planting). Similar to maize, soybean RFV was 1.19 ± 0.4 cm d^{-1} until the 3rd node when it increased to 3.31 ± 0.5 cm d^{-1} until maximum root depth occurred at the 13th node (813.6 °C d after planting). The maximum root depth was similar between crops ($P > 0.05$) and ranged from 120 to 157 cm across 18 experimental treatments, and 89–90 cm in two experimental treatments. Root depth did not exceed the average water table (two weeks prior to start grain filling) and there was a significant relationship between maximum root depth and water table depth ($R^2 = 0.61$; $P = 0.001$). Current models of root dynamics rely on temperature as the main control on root growth; our results provide strong support for this relationship ($R^2 > 0.76$; $P < 0.001$), but suggest that water table depth should also be considered, particularly in conditions such as the Midwest USA where excess water routinely limits crop production. These results can assist crop model calibration and improvements as well as agronomic assessments and plant breeding efforts in this region.

1. Introduction

Root systems affect plant growth, crop yields, and soil health, but studies on root characteristics are sparse. For example, plant breeding programs have focused on the selection of above ground plant traits for yield improvement (Tollenaar et al., 2004; Tollenaar and Lee, 2006) while giving little attention to the below-ground root morphology (Lynch, 2007). Among many root traits, root front velocity (RFV) and maximum depth are important because they determine the amount of water and nitrogen available for plant growth, as well as the amount of water and nitrogen vulnerable to leaching (Dunbabin et al., 2003). Indeed, deep, rapid-growth root systems may reduce losses of highly soluble nutrients such as nitrate (Lynch, 2013) because RFV closely matches the rate of nitrate leaching (York and Lynch, 2015).

Three-way interactions among crop genotype, management and environment determine maximum depth, RFV, and the ability of roots to extract water and nutrients. Relevant environmental factors include weather conditions (Watt et al., 2006), soil temperature and moisture (Weaver, 1926; Wang and Smith, 2004), ground water table (Stanley et al., 1980; Logsdon et al., 2009), soil-type and texture (Dwyer et al., 1996, Ball-Coelho et al., 1998), and nutrient availability (Lynch, 2007; Comas et al., 2013; Soylu et al., 2014). Management factors include the amount, type, placement and timing of fertilizer inputs (Dietzel et al., 2015; Lazicki et al., 2016), irrigation (Wang et al., 2014), tillage (Kaspar et al., 1991; Dweyer et al., 1996), row configuration (Whish et al., 2015) and others. Genotype factors include species identity (Borg and Grimes 1986) as well as variability between cultivars (Kaspar et al., 1984; Borg and Grimes, 1986; Yu et al., 2014). The mechanisms by

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which the above-mentioned factors affect root growth and final depth are complex, but soil conditions play a major role (Rich and Watt, 2013; Bao et al., 2014). For example, a compacted soil layer will reduce root growth, no matter if temperature or moisture are at optimum levels for root growth (Keating et al., 2003).

In a review study of 48 crops species, Borg and Grimes (1986) reported maximum root depths of 180–300 cm for maize, 150–200 cm for soybean, 150–300 cm for sorghum, 150–240 cm for rye, and 150–300 cm for wheat. The wide range reflects variable interactions among genotype, management and environment. The RFV exhibits similar variability: sorghum 2–4 cm d^{-1} (Monteith, 1986; Robertson et al., 1993; Whish et al., 2005; Manschadi et al., 2008), maize 2.7–6 cm d^{-1} (Taylor and Klepper, 1973; Dardanelli et al., 1997; Singh et al., 2010), soybean 3.5–4.5 cm d^{-1} (Stone et al., 1976; Kaspar et al., 1984), 2–7 cm d^{-1} for wheat and barley (Cohen and Tadmor, 1969) and chickpea 2.5–3.6 cm d^{-1} (Kashiwagi et al., 2015). This variability indicates that use of generic values (i.e., averages) for root parameters across environments may result in misleading agronomic assessments of plant and cropping system performance.

In the Midwest USA, recent work has shown major changes in above ground plant growth between new and old era cultivars (Duvick and Cassman, 1999; Ciampitti and Vyn, 2012). Our literature review for Iowa, USA revealed that information on root parameters has not been updated since the mid 1980s when management practices and plant traits were different than those used presently (Mason et al., 1982; Kaspar et al., 1984; Borg and Grimes, 1986). Iowa is a high production region in the USA (75% of the landscape is occupied with maize and soybean, which contribute 12–15% to national grain production; USDA-NASS, 2015) and is also a region with water quality challenges. Shallow water tables exist in this region (Zhang and Schilling, 2006; Schilling, 2007; Logsdon et al., 2009) and subsurface drainage systems have been installed in many Iowa fields to increase crop yields by removing excess water (Helmers et al., 2012). Improved knowledge about maize and soybean RFV and maximum depth could greatly assist agronomists and crop modelers in analyzing and designing sustainable cropping systems. In this study, we analyzed maize and soybean RFV and maximum root depth data from 20 field experiments covering six sites in Iowa. We asked the following questions:

1) What is the RFV and maximum depth of maize and soybeans crops?
2) How much time does it take roots to occupy the space between rows and reach their maximum depth?
3) To what degree can we predict root depth over time and what is the best predictor among soil, crop and weather variables?
4) Does the water table level affect maximum root depth?

We hypothesized that RFV would be different between maize and soybean crops given their different structures; maize has a fibrous root system, whereas soybean has taproot system (Feldman, 1994; Lersten and Carlson, 2004). We also hypothesized that air temperature could be a good predictor of root growth given its use in simulation models (Keating et al., 2003; Yang et al., 2017). Finally, we also hypothesized that shallow water tables inhibit root growth because the lack of oxygen reduces roots' ability to take up water and nutrients (Dickin and Wright, 2008; Florio et al., 2014).

2. Materials and methods

2.1. Experimental sites

In 2016, field experiments with maize and soybean were established at six Iowa sites spanning a broad range of temperature, precipitation and soil type (Figs. 1 and 2). Basic soil information for the sites is provided in Fig. 1. Three sites, Central-Ames, Northwest, and Southeast had different planting dates as a sub-factor; one site, Southeast, had different drainage systems as a sub-factor (with and without subsurface drainage), and two sites, Central-Kelley and Northeast, had no sub-factors (Table 1). The combination of sites, crops, and management practices resulted in 20 experimental units (Table 1). Experimental plots were set in a maize after soybean rotation using local management practices and well adapted cultivars. Maize plots were fertilized before or at planting (about 168 kg N/ha) while soybean plots did not receive nitrogen fertilizer. Crops were growing without supplemental irrigation. Each treatment was replicated three times at each site except Southeast, which had two replications. The size of replicated plots varied among sites; range from 360 to 3600 m^2, with the largest plots being in Northeast experimental site. Weeds, pest and diseases were suppressed by spraying herbicides, insecticides and fungicides when necessary.

2.2. Root measurements

The distance between crop rows was 76 cm (the conventional spacing in Midwest maize and soybean plantings) in all treatments and sites except Northeast soybean, for which row spacing was 25.4 cm (Exp. 14; Table 1). Root depth measurements were taken in the crop row (in-row) and in the center of two rows (center-row) approximately every 10–15 days from planting until maximum root depth was observed. In Southwest, Central-Kelley and Central-Ames measurements were made weekly while in Southeast, Northwest and Northeast every other week. On each sampling date, four sub-replicate measurements in each replicate were manually sampled using conventional 1.8 × 41 cm steel soil probes. Extensions were attached to the probe to capture roots to 180 cm depth (Fig. S1, panel a). Root depth was recorded in the field as the maximum visible root tip depth (Fig. S1, panel b).

When the maximum root depth was achieved per treatment a 6.20 × 120 cm hydraulic soil core probe with extensions to sample to 200 cm depth (Giddings Machine Company, Windsor CO, USA; Fig. S1, panel c) was used to validate manual samples in 16 out of the 20 treatments. In the lab, root depth for each core was recorded as the maximum visible root tip depth. Sampling areas were selected to avoid weed contamination and plot edges.

2.3. Weather, crop, and soil measurements

Maximum temperature, global solar radiation, and precipitation were recorded from network stations positioned at the border of each of the six experimental sites (Iowa Environmental Mesonet, IEM). Long-term (35-year) historical weather data were also available for each site.

All the experimental sites (except Northeast) were instrumented with Decagon (Pullman, WA, USA) soil moisture, temperature, and groundwater table sensors recording data every 30 min. Moisture and temperature sensors were positioned at two depth (15 and 45 cm) in each replication. Wells with groundwater table sensors were positioned at the borders of the experiments and were not replicated per treatment. Soil nitrogen measurements were taken from all replicated plots every two weeks (0–30 cm) and monthly (30–60 cm). In each replication, 10 sub-samples were taken from in-row and center-row positions and homogenized. Field-moist soil samples were analyzed for NO_3-N and NH_4-N concentrations (Hood-Nowotny et al., 2010).

Destructive above-ground crop sampling per replication was conducted approximately every two weeks. The sampling area for maize was 1.5 m^2 and for soybean 1 m^2. Plants were counted and cut at the ground level and analyzed to derive the following parameters: growth stage, leaf area index, maize leaf number, soybean node and pod number, biomass accumulation per plant tissue (leaf, stem, and storage organ including husk, cobs and kernels for maize, and pod and grains for soybeans), as well as carbon and nitrogen concentrations per plant tissue. Crop and soil sampling took place on the same day as root sampling. Therefore, crop and soil data were used to explore correlations between root depth and crop, soil, and weather variables (see below).