Dense Subsoils Limit Winter Wheat Rooting Depth and Soil Water Depletion

Rachel Breslauer\textsuperscript{a}, David J. Brown\textsuperscript{a}, William L. Pan\textsuperscript{a}, David R. Huggins\textsuperscript{b}, Isaac J. Madsen\textsuperscript{a}, and Haiying Tao\textsuperscript{a*}

\textsuperscript{a} Dept. of Crop and Soil Sciences, Washington State Univ., Pullman, WA 99164-6420, USA.  
\textsuperscript{b} USDA-ARS, Washington State Univ., Pullman, WA 99164-6421  

* Corresponding author: Haiying Tao, 245 Johnson Hall, Pullman, WA. Email: haiying.tao@wsu.edu. Phone number: 001-209-335-4389.

Core Ideas

- High subsoil bulk density increased odds of being RRD
- Winter wheat rooting depth was >200 cm when absent of RRD
- Greater post-harvest residual soil water was associated with less root density
- Grain yield was negatively associated with post-harvest residual soil water content

Keywords

Dryland soils, root growth, wheat, water stress, soil compaction, soil conservation

Abbreviations

Root restrictive depth, RRD

ABSTRACT

Dense subsoils pose a challenge to dryland winter wheat (\textit{Triticum aestivum} L.) production in the Palouse region of the semiarid northwestern USA. Subsoils, commonly fragipans and argillic horizons, may restrict root growth and limit crop access to critical stored soil water, but this phenomenon is not well characterized in the Palouse. During the 2017-2018 growing season, an
on-farm study of soil profiles in two commercial winter wheat fields in eastern Washington and northern Idaho was established to observe the effects of soil bulk density on winter wheat root system depth and subsoil water depletion. At harvest, grain yield, root density, soil bulk density, and post-harvest soil water and nitrogen content were measured to 120 cm at 15 cm segments in the profile. Root restrictive depth (RRD) was defined as the depth where root density was less than or equal to 0.25 intersections cm$^{-2}$ cross sectional area. Soil bulk density negatively affected root density and consequently increased the probability of shallow RRD. Shallow RRD was common, with 38% of profiles having RRD less than or equal to 105 cm. Post-harvest soil water content at the bottom of the measured profile [105-120 cm] was 41% higher in profiles with RRD of 90 cm when compared to non-restricted profiles. Yield declined with increase in post-harvest soil water content at [105-120 cm] depth. Findings indicate that dense subsoils can reduce stored soil water depletion by limiting root density and root system depth that, in turn, limits yield.

INTRODUCTION

Maintaining deep and high quality agricultural soils is critical to sustaining future dryland crop production in the Palouse agricultural region of the inland Pacific Northwest, USA. Deep soils are critical to a soil water bank sustaining crops throughout the growing season, typically July through September (Fig. 1). The Palouse is known for producing some of the highest quality and highest yielding dryland wheat [$Triticum aestivum$ (L.)] in the world, harvesting 3.9 million metric tons of grain per year (Washington Wheat Commission, 2017). The region is highly productive in part because it is the geographic center of a loessial deposit in the Pacific Northwest that in some areas can be as deep as 75 m (Schillinger et al., 2010; McCool and Busacca, 1999).
Despite having high production capacity in some areas, soil depth is highly variable across the region and within-fields. Loessial surface soils were unevenly deposited and formed over highly weathered paleosols throughout the past 15,000 years (McDaniel and Falen, 1994; McDaniel and Hipple, 2010). Paleosols in the Palouse contain duripans, layers of cemented silica and lime, argillic horizons, layers of silicate clay, or fragipans, and are consequently regarded as lower quality than younger loessial deposits (Busacca, 1989). Erosion in cultivated fields has further intensified within-field variability in soil depth. Southwesterly prevailing winds erode topsoil from exposed ridge tops and fast-moving surface water redistributes soil from steep (>40%) mid-slopes to lower lying areas (McCool and Busacca, 1999). It has been estimated that as many as 30% of upland areas in the Palouse have a restrictive soil in the root zone and could have a substantial effect on crop production (Busacca et al., 1985).

Agricultural system productivity depends on soil physical quality, including a soil's strength and ability to support crop growth, transmit fluids, and store resources in the root zone (Topp et al., 1997). Some paleosols in the Palouse region have poor physical quality because they are dense, with little porosity, and have high bulk densities; for example, fragipans typically have bulk densities around 1.75 g cm\(^{-3}\) (McDaniel and Falen, 1994). As soil bulk density increases, the soil’s impedance to root elongation increases. In order to elongate, roots must exert more force on the bulk soil thus reducing root elongation rates (Bengough et al., 2011). Consequently, dense soils within crop root zones may limit root elongation, thereby reducing soil exploration by the root system (McCool et al. 1999; Busacca et al., 1985; Winters and Simonson, 1951). The root restrictive depth (RRD) is the depth to a soil layer that has physical properties, such as bulk density, that restricts root penetration deeper into the soil profile (Soil Survey Staff, 2014). It was defined as the depth where root density was less than or equal to 0.25 intersections...
cm² cross sectional area. Variable depth to a dense subsoil could contribute to spatially variable RRD for a particular crop.

There is evidence that exposed dense subsoils can reduce crop productivity and subsoil water use. Busacca et al. (1985) demonstrated that wheat yield losses due to topsoil erosion in the Palouse region were dependent on soil type, and that losses due to erosion were 28% higher in profiles with impermeable B horizons when compared to profiles that had B horizons with few limitations to rooting and water infiltration. Pan and Hopkins (1991) observed lower yield, root length density and soil water depletion in barley (*Hordeum vulgare* L.) grown at an eroded ridgetop position where there was a compact B horizon in the profile. Poor subsoil water use can negatively impact crop yields in dryland wheat production regions. Research in Australian dryland wheat production has demonstrated that efficient deep soil water use is associated with high yields in water limited environments (Kirkegaard et al. 2007; Manschadi et al. 2006).

However, no studies have quantified how dense subsoils, such as paleosols, affect rooting depth and stored water use by winter wheat, and its impact on yield and quality.

The present study aimed to understand if dense subsoils impede winter wheat root system growth and access to subsoil water in the Palouse region. The objectives were to i) quantify the effect of soil bulk density and soil water content on wheat root restriction, ii) characterize the within-field spatial variability of RRD, iii) examine the impact of root restriction on stored soil water use, and iv) assess the effect of stored soil water use on winter wheat grain yield, aboveground biomass, and grain protein concentration.

**MATERIALS AND METHODS**

**Field Sites**
This study was conducted on two, 20.23 hectare hillslopes, in two commercial dryland winter wheat fields in Whitman County, WA, approximately 8 km northeast of Albion, WA, and Latah County, ID, approximately 8 km south of Troy, Idaho, during the 2017-2018 growing season (Table 1). Exact coordinates for each site are not provided to protect collaborating farm privacy, but can be made available after request from the authors. Study site boundaries within each field were chosen with producers to be representative of within-field variability and accessible to sampling equipment at harvest. Both sites have a xeric precipitation pattern and receive 59% of annual precipitation from September to February and 38% of annual precipitation from March to May (AgWeatherNet, 2018). The 2017-2018 growing season had greater than the ten-year average precipitation from September to February (68% of annual) and less than the ten-year average precipitation from March to May (31% of annual) (Fig. 1). The Latah site is estimated to receive 584-635 mm annual precipitation based on a survey conducted by Barker (1981), but a more accurate estimate of precipitation at the Latah site is not possible due to the lack of nearby weather stations. The Whitman site was predominantly composed of soils of the Palouse series (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls), whereas the Latah site was primarily composed of soils of the Larkin and Taney soil series (fine-silty, mixed, superactive, mesic Ultic Argixerolls; fine-silty, mixed, superactive, frigid Vitrandic Argixerolls). The Whitman site received uniform nitrogen (N) application in fall 2017. The Latah site received uniform N application in fall 2017 and three different rates of N for three zones in spring 2017. The variable rate spring N was determined by yield goal method developed using a history of yield maps generated by a combine-mounted yield monitor.

Profile Selection
Because the distribution and depth of dense subsoils in the study sites were unknown, this study used a satellite imagery-guided approach to identify sampling locations within each site. Numerous relationships have been established between crop water stress and spectral indices, including the Normalized Difference Vegetation Index and Canopy Chlorophyll Content Index; both indices are highly related to winter wheat yield (Barnes et al., 2000; Zargar et al., 2011; Magney et al., 2017). Study sites were delineated into zones that represented various stress level and spatial variability of yield based on historical reflectance patterns. Twenty zones with average 1-ha size were determined using a k-means clustering analysis of in-season (March-August) 5m resolution RapidEye satellite imagery (Berlin, Germany) from 2009-2015. RapidEye images are composed of five bands: blue (440-510 nm), green (520-590 nm), red (630-685 nm), red edge (690 – 730 nm), and near infrared (760-850 nm). All images were clipped to the study area boundary determined with producers prior to analysis. Band value variability was reduced to twenty principal components using the stats package in R (R Core Team, 2017). A k-means clustering analysis, which maximizes within group homogeneity and among group heterogeneity, was conducted using the stats package to classify the site area into twenty zones using the previously generated principal components. One random sampling location was selected from each zone, for a total of twenty sampling locations per site, and location coordinates were uploaded to a handheld GPS unit (Trimble Geo7x, Trimble, Ltd., Sunnyvale, CA). Sampling locations were then identified in the field using the handheld GPS unit and flagged. Soil and plant samples were collected within a 2.5 m radius of the predetermined flagged profile location.

Data Collection

Soil samples at each sampling location were collected immediately following winter wheat harvest. A hydraulic sampling probe equipped with a 3.18 cm inside diameter tube was
used to collect a continuous 120 cm core. A total of five cores (120 cm depth) were collected at each sampling location. Three replicate cores were collected on the top of a plant in-row to measure root density, one core was collected between-row to measure post-harvest soil nitrate-N concentration, and another core was collected between-row to measure bulk density and soil water content. Cores were discarded and resampled if they became visibly compacted during the sampling process.

Root density from the in-row cores was measured using the core break method, which was a feasible method for estimating root density in wheat (Bohm, 1979; Bennie et al., 1987). In the core break method, roots that appear on one face of a broken soil core are counted and the root density is calculated as root counts per unit area. Cores (120 cm depth) were cut into cross-sections using a knife at 15 cm segments and the number of root intersections visible on one face of the cross-section was recorded. Root density was calculated by dividing the root count by the core cross-sectional area, 7.92 cm$^2$. Reported root density is the average of 3 replicates for each depth unless stated otherwise.

Intact cores to measure bulk density and soil water content were sampled to a 120 cm depth and split at 15 cm segments using a knife for a total of eight measurement depths per profile. Samples were stored in airtight plastic bags during transport to preserve water content. Samples were broken and put into large tins for drying for 24 hours at 105°C. Sample mass was recorded prior to and after being dried. Dry core weight was used to calculate soil bulk density in g cm$^{-3}$. Post-harvest gravimetric soil water content was calculated in g g$^{-1}$ as the mass difference between the fresh core mass and dry core mass on a dry mass basis. The gravimetric soil water content was converted to volumetric units (mm) using the bulk density of the soil measured for each segment.
Soil was sampled for KCl extractable nitrate-N concentration and gravimetric water content to a 180 cm depth and split at 30 cm segments for a total of six measured depths per profile to quantify nitrate content and thus determine potential nitrate leaching below the root zone at each sampling location.

Biomass and grain yield were measured at crop maturity from 3 representative 1 m² quadrats. Plants were cut by hand 2 cm from the soil surface using a scythe. Samples were dried for 48 hours in a glass house that reached approximately 50°C during the day, and then weighed. Samples were then threshed to determine grain yield and harvest index was calculated by dividing grain yield by the aboveground biomass yield (Passioura, 1997). Grain protein and water concentration was measured using an NIR analyzer on whole grain samples (Model #DA7250, Perten Instruments, Hägersten, Sweden). Grain protein concentration was adjusted to a standard 12% grain moisture.

**Statistical Analyses**

The metrics used to assess whether soil bulk density affected the root system were i) analysis of the relationship between soil bulk density and root density at discreet depths in the profile; and ii) analysis of the effect of soil bulk density on rooting depth and assessment the within-field spatial variability of rooting depth. The response of root density to soil bulk density, profile depth segments, soil water content, and study site was fitted to a multiple linear regression with least square estimation using *stats* package in R (R Core Team, 2017) (Eq. 1). Profile depth of segments was included in Eq. 1 because the root architecture of field-grown wheat plants includes many roots with shallow root angles and few roots with steep root angles thus causing root density to change with profile depth segments (Passioura, 1983). Soil water content was included in Eq. 1 to account for its effect on soil impedance to root growth (Vaz et al., 2011).
\[ R_{id} = \beta_1 r + \beta_2 D_{id} + \beta_3 \Theta_{id} + \beta_4 [r \times D_{id}] + \beta_5 [r \times S] \]  

[Eq. 1]

where

\( R_{id} = \) average root density (no/cm²) at \( dth \) \((d=1-8)\) depth in \( ith \) \((i=1-40)\) profile;

\( r = \) profile depth (cm) of the bottom of the soil core segment \((d=15 \text{ cm to } 120 \text{ cm at } 15 \text{ cm intervals})\);

\( D_{id} = \) bulk density (g cm⁻³) observed between the surface and \( dth \) depth in \( ith \) profile;

\( \Theta_{id} = \) gravimetric water content (%) at \( dth \) depth in \( ith \) profile;

\( S = \) study site (Latah, Whitman).

The RRD of a particular soil can be inferred from the distribution of crop roots throughout the soil profile. The RRD was defined as the profile depth where root density was 0.25 intersections cm⁻² cross sectional area or lower. A binary logistic model was used to analyze the probability of \( R_{id} \) being less than or equal to 0.25 intersections cm⁻² cross sectional area (Eq. 2). Variables were the profile segment depth, soil bulk density in profile \((i)\) at depth \((d)\) and site \((S)\). Site was also included as a factor because different winter wheat varieties were grown at each site (Table 1) and genotype can significantly affect wheat root system architecture (Manschadi and Hammer, 2008; Nakhforoosh et al., 2014). Parameter estimates, confidence intervals, and odds ratios were generated using the \textit{stats} package in R. Hosmer-Lemeshow’s goodness of fit and likelihood ratio tests were conducted to assess model goodness-of-fit (Hothorn et al., 2015; Lemeshow and Hosmer, 1982).

\[ T_{id} = \beta_1 r + \beta_2 D_{id} + \beta_3 S \]  

[Eq. 2]

where
T_{id} = a binary variable which is 1 when the soil core at \( dth \) depth in \( ith \) profile is the RRD (\( R_{id} \leq 0.25 \) intersections per cm\(^2\) core cross sectional area) and 0 otherwise;

\( r = \) profile depth (cm) of the bottom of the soil core (\( d = 15\) cm to 120 cm at 15 cm intervals);

\( D_{id} = \) bulk density (g cm\(^{-3}\)) at \( dth \) depth in \( ith \) profile;

\( S = \) study site (Latah, Whitman).

Soil water content at the bottom of the measured profile [105-120 cm] following harvest was used as an indicator of soil water depletion throughout the season. An analysis of variance was conducted using the \textit{stats} package in R to assess if post-harvest soil water content at the bottom of the measured profile [105-120 cm] was significantly greater in profiles with shallow RRD when compared to profiles with non-restricted root systems (R Core Team, 2017). Mean separation tests to examine the significance between the groups were performed using Tukey option. To measure the agronomic impact of soil water depletion, correlations between post-harvest soil water content at the bottom of the measured profile [105-120 cm] and winter wheat agronomics (i.e. grain yield, aboveground biomass, and grain protein concentration) were calculated. Relationship strength was assessed by calculating Pearson’s correlation coefficients and significance using the \textit{Hmisc} package in R (Harrell and Dupont, 2017). Significance was measured at the 95% probability level unless stated otherwise.

**RESULTS AND DISCUSSION**

**Bulk Density, Soil Water Content, and Root Density**

High variation in bulk density was observed in each field, with values ranging from approximately 1.00 g cm\(^{-3}\) to greater than 1.90 g cm\(^{-3}\) with a mean of 1.52 g cm\(^{-3}\) (Fig. 2b).

Argillic horizons are typically thought to have bulk densities of 1.65-1.75 g cm\(^{-3}\) (Brooks et al., 2012). Approximately 37% and 21% samples in Latah and Whitman fields, respectively, had a
bulk density greater than 1.65 g cm\(^{-3}\), and 22% and 9% samples in Latah and Whitman fields, respectively, had a bulk density greater than 1.75 g cm\(^{-3}\). High bulk density suggested that substantial amount of sample locations had less air-filled pore space than dense soils previously measured in this region. The range in soil water content observed at all depths in each field was similar (Fig. 2c). Soil water content at all depths of sample locations ranged from 6.2 to 59.1 mm (median = 27.1 mm) in the Latah site and ranged from 5.1 to 65.4 mm (median = 26.5 mm) in the Whitman site. Median root density for all samples was 1.10 intersections cm\(^{-2}\) with 25% of observations having 0.38 or fewer intersections cm\(^{-2}\) (Fig. 2a). The root density at depth exhibited typical root morphology with highest average root density observed in surface cores and decreased as soil depth increased. Large spatial variability of root density was found at all depths in both Whitman and Latah fields (Fig. 3).

**Effect of Soil Bulk Density on Root Restriction**

The multiple regression model explained a high proportion of variation in root density (Table 2). Results indicated that depth, post-harvest soil water content, bulk density, site and the interaction between depth and site were significant factors affecting winter wheat root density.

Results from Eq. 1 quantified the change in root density as bulk density increased. Holding all other variables constant, as bulk density increased 0.1 g cm\(^{-3}\) (average bulk density = 1.52 g cm\(^{-3}\)), the root density decreased by 0.55 intersections cm\(^{-2}\) on average (Table 2). Negative coefficient for the interaction between bulk density and depth indicating that an increase in soil bulk density decreased root density more at shallow profile depths than at deeper profile depths. Findings from Eq. 1 demonstrate that there are soils that limit root density in commercial farm fields. These findings, for the first time, confirmed suppositions that dense soils in the root zone limit crop root systems in the Palouse region.
Additional significant variables in Eq. 1 were: post-harvest water content, site, depth, and the interaction between depth and site. Holding all other variables constant an increase in soil water content 0.1 g g\(^{-1}\) (average soil water content = 0.12 g g\(^{-1}\)) was associated with a root density decrease of 3.75 intersection cm\(^{-2}\) (Table 2). This finding could be attributed to low root density causing poor water extraction efficiency from the subsoil. Root proximity to soil water resources is necessary for water uptake and deeper root systems can increase water use (Tennant and Hall, 2001). Consequently, poor root proliferation may have limited crop soil water depletion. Root density also decreased significantly with profile depth. This is likely because the root angles and numbers vary with depth in field-grown wheat plants (Passioura, 1983). Additionally, there was a significant interaction between depth and site. Root system architecture can vary substantially across wheat varieties (Manschadi and Hammer, 2008; Nakhforoosh et al., 2014). It is possible that root system architectures varied significantly amongst the varieties grown at the two sites (Table 1).

The likelihood ratio test for Eq. 2 was significant, indicating that profile depth, bulk density, and site significantly improved model goodness of fit compared to the null model (Table 3). The results of the Hosmer-Lemeshow test were non-significant, indicating that there is no evidence of poor model fit. The odds ratios for variables in Eq. 2 were: bulk density (1.37), profile depth (1.07), and site (0.48). As soil bulk density increased, the likelihood of root restriction at that depth increased slightly. For example, increasing soil bulk density 0.25 g cm\(^{-3}\), the soil was 1.37 times more likely to be RRD (Table 3). The result of Eq. 2 indicates that an increase in bulk density significantly increases the odds of the soil being restrictive to rooting depth. Additional variables in Eq. 2 had significant effects on the odds of restricted rooting depth in the soil profile. Profile depth had the most notable effect; increasing profile depth only 5 cm
increased the likelihood of root restriction at that depth five-fold. This finding is consistent with
the root density model (Eq. 1) where root density decreased significantly with profile depth
(Table 2). The likelihood of root restriction also differed between the two sites. Root restriction
was 53% more likely at the Whitman site than at the Latah site.

Previous studies have established that soils with excessive impedance can limit root
elongation rate (Kirkegaard et al. 1992), root length density (Nosalewicz and Lipiec, 2014), and
total root mass (Masle and Passioura, 1987). There are opportunities to improve our
understanding of how multiple physical properties of dense subsoils in the Palouse affect root
density and RRD. Models in this study focused on soil bulk density as the primary soil physical
property limitation to root elongation and penetration through the soil. These models could be
improved by accounting for other factors that affect soil impedance to root growth, such as soil
texture and pore distribution. Jones (1983) demonstrated that soil texture affected the critical
bulk density at which root growth stops, and that the critical bulk density was generally lower for
soils with high clay content. Additionally, understanding the role of macropore channels in root
penetration of dense soils would be an important step to study RRD and its effects on crop
growth. White and Kirkegaard (2010) found that more than 80% of roots in a densely structured
subsoil (> 0.9 m) were confined to macropores, and that very few roots penetrated the bulk soil
at these depths. Few macropores could also cause oxygen deficient rhizosphere conditions in the
spring when soils are wet. Anoxic and hypoxic conditions can cause root death early in the
season and flooding sensitive species may fail to compensate with other root growth after
flooded conditions subside (Tang and Kozlowski, 1981; Kozlowski, 1984). Accounting for these
additional effects would more clearly demonstrate what soil physical properties limit root growth
and consequently crop yield and quality in the Palouse region.
Spatial Variability of Root Restrictive Depth

Seventy percent of sampled profiles had an RRD less than or equal to 120 cm, while 50% and 25% of profiles had an RRD less than or equal to 105 cm in the Whitman and Latah sites respectively (Fig. 4). The minimum RRD at the Whitman site was 45 cm and 90 cm at the Latah site. Only 30% of sampled profiles showed no restriction within 120 cm of the soil surface.

Shallow RRD was more common than expected based on previous estimates in the Palouse region. Based on soil loss estimates, Busacca et al. (1985) estimated that 30% of upland areas in the eastern Palouse have a restrictive soil in the root zone, whereas for the two sites in this study we found that 70% of studied profiles had RRD shallower than 120 cm. This could be due, in part, to the small scale of this study. It is notable that a high proportion of profiles had RRD shallower than 120 cm because unrestricted cereal root systems can develop as deep as 200 cm (Manschadi et al. 2013). Current Washington State University nutrient management recommendations account for winter wheat crops drawing from N and water in the soil to 200 cm in the absence of obvious restrictive soils (Koenig, 2005). In contrast, results shown here suggest that 25% of profiles in the Whitman site and 35% of profiles in the Latah site had the potential to develop root systems below 120 cm. Between the two sites, we found differences in the proportion of profiles with RRD of 120 or greater (Latah, 75%; Whitman, 50%). More investigations into how bulk density affects root density and RRD across years and multiple sites are needed to understand how variable rooting depth is within fields in the Palouse region.

Impact of Root Restriction on Stored Soil Water Use

Sites with an RRD of 90 cm had higher post-harvest water content [105-120 cm] than in non-restricted profiles (Fig. 5). In fact, median soil water content at this depth was 41% higher in profiles with RRD of 90 cm when compared to non-restricted profiles. This suggests that deep
winter wheat root systems deplete the subsoil of available water more than shallow root systems. Similar results were found in barley grown in the Palouse region. Pan and Hopkins (1991) found significantly greater post-harvest soil water content [105-120 cm] in a profile with a shallow root system relative to profiles where crop roots reached deeper in the profile. They observed that the post-harvest soil water content [105-120 cm] in an eroded ridgetop profile with shallow RRD was 28% higher than a non-restricted profile at the same depth. Maaz et al. (2017) suggested that a plateau in WW yields with increasing annual precipitation in the eastern Palouse may be due to lower water infiltration efficiency and lower subsoil water extraction. In a controlled column study, Nosalewicz and Lipiec (2014) found lower cumulative water uptake from deep layers in the column where soils were sufficiently dense to limit root length density. Similarly, we found that post-harvest soil water content at discrete soil depths had a negative effect on root density (Table 2). Previous studies had reported that sufficient soil water content during early growth can reduce soil impedance to root growth (Masle and Passioura, 1987). However, this research suggested that higher post-harvest soil water content may instead be a product of poor water extraction efficiency in soil layers with low root length density. Soil texture also plays an important role in determining the plant available water content of the soil because permanent wilting point is texture dependent. Ratliff et al. (1983) found that the volumetric water content at permanent wilting point increased with clay content: silty clay loam (15%), silty clay (20%), and clay (22%). Profiles with shallow RRD could also have high clay content subsoils, further limiting subsoil water depletion.

Due to the complex nature of lateral water movement in the Palouse region it is difficult to say with certainty that soil water content in [105-120 cm] was below the root zone for the entirety of the growing season. Perched water tables can form above fragipans and argillic
horizons during the winter and can persist until May (McDaniel and Falen, 1994; McDaniel et al. 2008), rewetting subsoils. Grain filling in the eastern Palouse typically occurs in early June suggesting that winter wheat water uptake is still occurring far after lateral water flow is common. Anecdotally, farmers and researchers in the region have observed side slopes rewetting after harvest before fall precipitation resumes. While it is unlikely that lateral water flow rewetted subsoil late in the season, we cannot say with certainty that it was not a factor in determining post-harvest subsoil water content in this study.

Post-harvest soil water content [105-120 cm] was significantly positively correlated with subsoil nitrate-N concentration [90-180 cm] (Fig. 6). This finding suggests that field areas with poor subsoil water depletion may also have more nitrate-N leaching losses from the root zone. By limiting root system exploration of the soil, dense subsoils may limit crop access to and uptake of multiple nutrients.

**Effect of Stored Water Use on Winter Wheat Agronomics**

Grain yield and post-harvest soil water content [105-120 cm] were significantly negatively correlated (Table 4). Neither biomass yield, harvest index, nor grain protein concentration were significantly correlated with post-harvest soil water content [105-120 cm]. This finding suggests that high subsoil water content after harvest was associated with crop stress and grain yield losses. Other studies have demonstrated the value of subsoil water use to grain yield in Palouse wheat systems. Schillinger et al. (2008) found that winter wheat grain yield increased 154 kg ha\(^{-1}\) for every additional cm of water beyond that needed for vegetative growth in eastern Washington. An earlier study conducted in eastern Washington found similar yield gains of 149 kg ha\(^{-1}\) for every additional centimeter of water (Leggett, 1959; Schillinger et al., 2008). For both studies, stored water had a significant effect on yield. Yield gains with an
additional 1 cm of soil water were lower than an additional 1 cm of spring rain in these two studies. However, Schillinger et al. (2008) notes that more of the total water supply to the crop comes in the form of stored soil water. Consequently, stored soil water was more important for determining wheat yield than spring rain.

By limiting RRD and soil water depletion, dense subsoils likely limited grain yield in this study. Because shallow RRD affected a large proportion of studied profiles (Fig. 4) and shallow RRD can negatively impact stored water use by the crop (Fig. 5), shallow RRD caused by dense subsoils may be an important but understudied yield limiting factor in the Palouse region. More work is needed to thoroughly investigate how subsoils within the root zone affect crop use of stored soil water throughout the season.

While other studies have shown crop yield losses on eroded, weathered soil profiles (Busacca et al. 1985) as well as shallow root systems and lower yields on eroded ridgetop soils (Pan and Hopkins, 1991), this is the first field survey study in the Palouse that has quantified the effect of soil bulk density on root density and RRD. Moreover, this finding demonstrates that there are sufficiently dense soils in the crop root zone that limit root growth in commercial farm fields. The key to maintaining crop productivity in field areas with dense subsoils is preventing erosion of surface soils that support root growth. To maintain deep soils, farmers must manage soils to minimize erosion. While some field areas are already affected by dense subsoils, preventing further surface soil loss may be critical to sustaining winter wheat productivity in the Palouse region.

CONCLUSION

Dense subsoils play a role in limiting winter wheat root density and RRD. This is the first study in the Palouse region to quantify the effect of dense subsoils on winter wheat root density.
As soil bulk density increased the likelihood of the soil being RRD increased significantly. Of all measured profiles, 70% had some level of restriction (RRD ≤ 120 cm) while 38% of profiles were more severely restricted (RRD ≤ 105 cm). Low root density in profiles with shallow RRD likely limited the root system’s ability to extract soil water efficiently. This was especially true in profiles with RRD of 90 cm where post-harvest soil water content at the bottom of the measured profile [105-120 cm] was 41% higher than in non-restricted profiles, suggesting less water uptake in these areas. Use of stored soil water is critical to cultivating winter wheat through the dry season and RRD within rootzone caused by dense subsoils likely lead to lower grain yields in this study. Yields reduced with post-harvest subsoil water content increases when the RRD was shallower than 120 cm. More investigation is needed to characterize how within-field variation in RRD affects yield spatial variability across years so we better understand how restricted subsoil water depletion can contribute to yield losses and grain quality such as protein content and test weight. Future studies should also include more fields across rainfall gradients in PNW to quantify the differences in RRD effect on yield and grain quality under different annual rainfall conditions in Palouse region.

ACKNOWLEDGMENTS

This work was supported by the USDA National Institute of Food and Agriculture [Hatch project 1014527], USDA National Institute of Food and Agriculture Food Security Program grant [Award number 2016-68004-24769], Washington State University New Faculty Seed Grant, and Otto and Doris Amen Dryland Research Endowment. The authors thank farmers participation and their generosity in providing land for this research. We also thank Dr. Linda R. Klein for valuable writing advice and editing the manuscript.

REFERENCES
AgWeatherNet. 2018. Washington State University’s AgWeatherNet. Pullman, WA, USA. http://weather.wsu.edu/awn.php (accessed 5 Dec. 2018).

Barker, R.J. 1981. Soil survey of Latah County area, Idaho. US Govt. Print. Office, Washington, DC.

Barnes, E.M., T.R. Clarke, S.E. Richards, P.D. Colaizzi, J. Haberland, et al. 2000. Coincident detection of crop water stress, nitrogen status and canopy density using ground based multispectral data. In: P.C. Robert et al., editors, Proceedings of the 5th international conference on precision agriculture and other resource management. ASA, Madison, WI. p. 1-15 ref. 19.

Bengough, A.G., B.M. McKenzie, P.D. Hallett, and T.A. Valentine. 2011. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. J. Exp Bot. 62(1): 59-68.

Bennie, A.T.P., H.M. Taylor, P.G. Georgen. 1987. An assessment of the core-break method for estimating rooting density of different crops in the field. Soil Till. Res. 9(4): 347-353.

Bohm, W. 1979. Methods of studying root systems. Springer. Berlin.

Brooks, E.S., J. Boll, and P.A. McDaniel. 2012. Hydropedology in seasonally dry landscapes: The Palouse region of the Pacific Northwest USA. In: H. Lin, editor, Hydropedology: Synergistic integration of soil science and hydrology. Academic Press, Waltham, MA. p. 329-350.

Busacca, A.J. 1989. Long Quaternary record in eastern Washington, U.S.A., interpreted from multiple buried paleosols in loess. Geoderma. 45: 105-122.

Busacca, A.J., D.K. McCool, R.I. Papenndick, and D.L. Young. 1985. Dynamic impacts on productivity of soils in the Palouse. In: American Society of Agricultural Engineers, editor, National symposium on erosion and soil productivity. p. 152-169.

Harrell, F.E., and C. Dupont. 2017. Hmisc: Harrell miscellaneous. v 4.0-3. R Foundation for Statistical Computing, Vienna, Austria.

Hothorn, T., A. Seileis, R. Farebrother, C. Cummins, G. Millo, and D. Mitchell. 2015. Testing linear regression models- Package “Lmtest.” R Foundation for Statistical Computing, Vienna, Austria.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. SSAJ. 47: 1208-1211.

Kirkegaard, J.A., H.B. So, R.J. Troedson. 1992. The effect of soil strength on the growth of pigeonpea radicles and seedlings. Plant Soil. 140:65-74.

Kirkegaard, J.A., J.M. Lilley, G.N. Howe, and J.M. Graham. 2007. Impact of subsoil water use on wheat yield. Aust. J. Agric. Res. 58: 303-315.

Koenig, R.T. 2005. Dryland winter wheat: Eastern Washington nutrient management guide. EB 1987. Washington State Univ. Ext., Pullman.
Kozlowski, T.T. 1984. Plant responses to flooding of soil. BioScience. 34(3):162-167.

Leggett, G.E. 1959. Relationships between wheat yield, available moisture and available nitrogen in eastern Washington dry land areas. Washington Agricultural Experiment Station Bull. 609. Washington State University, Pullman, WA.

Lemeshow, S., and D.W. Hosmer. A review of goodness-of-fit statistics for use in the development of logistic regression models. Am. J. Epidemiol. 1982. 115:92–116.

Maaz, T. M., W. Schillinger, S. Machado, E. Brooks, J. Maynard-Johnson, I. L. E. Young, F. L. Young, I. Leslie, A. Glover, I. J. Madsen, A. Esser, H. Collins, , and W.L. Pan. 2017. Impact of climate change adaptation strategies on winter wheat and cropping system performance across precipitation gradients in the Inland Pacific Northwest, USA. Front. Environ. Sci. 5:23. doi: 10.3389/fenvs.2017.00023

Magney, T.S., Eitel, J.U.H., and Vierling, L.A. 2017. Mapping wheat nitrogen uptake from Rapideye vegetation indices. Precis. Agric. 18:429-451.

Manschadi, A.M., J. Christopher, P. deVoil, and G.L. Hammer. 2006. The role of root architectural traits in adaptation of wheat to water-limited environments. Functional Plant Biology. 33: 823-837.

Manschadi, A. M., and G.L. Hammer. 2008. Genotypic variation in seedling root architectural traits and implications for drought adaptation in wheat (Triticum aestivum L.). Plant Soil. 303: 115-129.

Manschadi, A.M., G.G.B. Manske, and P.L.G. Vlek. 2013. Root architecture and resource acquisition: Wheat as a model plant. In: A. Eshel et al., editors, Plant roots: the hidden half 14th ed. Chapman and Hall, Boca Raton, FL. p. 229-245a.

Masle, J., and J.B. Passioura. 1987. The effect of soil strength on the growth of young wheat plants. Aust. J. Plant Physiol. 14: 643-656.

McCool, D.K., and A.J. Busacca. 1999. Measuring and modelling soil erosion and erosion damages. In: E.L. Michalson et al., editors, Conservation farming in the United States: The methods and accomplishments of the STEEP program. CRC Press LLC, Boca Raton, FL. p. 23-56.

McDaniel, P.A., and Falen, A.L. 1994. Temporal and spatial patterns of episaturation in a Fragixeralf landscape. SSSAJ. 58: 1451-1457.

McDaniel, P.A., and Hipple, K.W. 2010. Mineralogy of loess and volcanic ash eolian mantles in Pacific Northwest (USA) landscapes. Geoderma. 154: 438-446.

McDaniel, P.A., M.P. Regan, E. Brooks, J. Boll, S. Barndt, A. Falen, S.K. Young, and J.E. Hammel. 2008. Linking fragipans, perched water tables, and catchment-scale hydrological processes. Catena. 73: 166-173.

Nakhforoosh, A., H. Grausgruber, H. Kaul, and G. Bodner. 2014. Wheat root diversity and root functional characterization. Plant Soil. 380: 211-229.
Nosalewicz, A., and J. Lipiec. 2014. The effect of compacted soil layers on vertical root
distribution and water uptake by wheat. Plant Soil. 375(1-2): 229-240.

Pan, W. L., and A.G. Hopkins. 1991. Winter barley development, N and P use: responses to
no-till and N management at slope positions of eroded toposequences. Plant Soil. 135:
21-29.

Passioura, J.B. 1983. Roots and drought resistance. Agric. Water Management. 7: 265-280.

Passioura, J.B., 1977. Grain yield, harvest index, and water use of wheat. J. Aust. Inst. Agric.
Sci. 43: 117-120.

Ratliff, L.F., J.T. Ritchie, and D.K. Cassel. 1983. Field-measured limits of soil water
availability as related to laboratory-measured properties. SSAJ.47: 770-775.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation
for Statistical Computing, Vienna, Austria. https://www.R-project.org/ (accessed 20
Feb. 2019).

Schillinger, W.F., R.I. Papendick, and D.K. McCool. 2010. Soil and water challenges for
Pacific Northwest agriculture. In: T.M. Zobeck and W.F. Schillinger, editors, Soil and
water conservation advances in the United States. SSSA Special Publication 60.
Madison, WI. p. 47-79.

Schillinger, W.F., S.E. Schofstoll, and J.R. Alldredge. 2008. Available water and wheat grain
yield relations in a Mediterranean climate. Field Crops Res. 109: 45-49.

Soil Survey Staff. 2014. SSURGO metadata—Table column descriptions report.
SSURGO/STATSGO2 structural metadata and documentation. NRCS, USDA.
https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_05
3631 (accessed 01 Mar. 2019).

Tang, Z.C., and T.T. Kozlowski. 1981 Some physiological and morphological responses of
Quercus macrocarpa seedlings to flooding. Can. J. For. Res. 12: 196-202.

Topp, G.C., W.D. Reynolds, F.J. Cook, J.M. Kirby, and M.R. Carter. 1997. Physical
attributes of soil quality. In: E.G. Gregorich and M.R. Carter, editors, Soil quality for
crop production and ecosystem health. Developments in soil science, vol. 25. Elsevier,
New York, NY. p. 21-58.

Trimble. 2019. Trimble Geo7X handheld datasheet. Trimble Navigation Ltd., Sunnyvale,
CA. https://drive.google.com/file/d/0BxW3dqQ5gdnTRkh0STNzUTF3b0k/view
(accessed 20 Feb. 2019)

Vaz, C.M.P, J.M. Manieri, I.C. de Maria, and M. Tuller. 2011. Modeling and correction of
soil penetration resistance for varying soil water content. Geoderma. 166: 92-101.

Washington Wheat Commission. 2017. Washington Wheat Facts. http://wagrains.org/all-
about-wheat/varieties-of-wheat/ (accessed 12 Dec. 2018)
White, R.G. and J.A. Kirkegaard. 2010. The distribution and abundance of wheat roots in a dense, structured subsoil – implications for water uptake. Plant Cell Environ. 33: 133-148.

Winters, E. and R.W. Simonson. 1951. The subsoil. In: A.G. Norman, editor, Advances in agronomy, vol. 3. Elsevier, Amsterdam. p.1-92.

Zargar, A., R. Sadiq, B. Naser, and F.I. Khan. 2011. A review of drought stress. Environ. Rev. 19: 333-349.

Fig. 1. Total monthly precipitation in the 2017 to 2018 growing season compared to the ten-year average (2008-2018) near the Whitman site (AgWeatherNet, 2018).

Fig. 2. Statistical characterization of (a) root density (three replications per sampling location were taken for root density observation), (b) soil bulk density, and (c) post-harvest soil water content measurements in two commercial winter wheat sites in the Palouse agricultural region, sampled in 2018. Cores were sampled post-harvest at 15 cm segments for [0-120 cm] in the profile. The horizontal line within the box of the box-and-whisker plots represents the median; the bottom edge of the box is the 25th percentile; and the top edge is the 75th percentile. The end of the top whisker represents the 90th percentile; the end of the bottom whisker is the 10th percentile. Dots above and below the ends of the whiskers are the outliers.

Fig. 3. Distribution of winter wheat root density in each of 8 sampled depths [0-120 cm]. Samples were collected from forty soil profiles in two sites in 2018 (Latah, total n = 478; Whitman, total n = 460). The vertical line inside the box of the box-and-whisker plots represents the median; the left edge of the box is the 25th percentile; and the right edge is the 75th percentile. The end of the right whisker represents the 90th percentile; the end of the left whisker is the 10th percentile. Dots to the left and right of the ends of the whiskers are the outliers.

Fig. 4. Distribution of winter wheat root restrictive depth in forty soil profiles in two commercial winter wheat sites. Profiles where root restriction was not observed within 120 cm of the surface are listed as “Not restricted.”

Fig. 5. Post-harvest water content at [105–120 cm] depth in profiles with different root restrictive depth in two commercial winter wheat sites in the Palouse agricultural region, sampled in fall 2018. Boxes followed by the same letter are not significantly different (p > 0.05). Only 1 sampling location had root restrictive depth less than 75 cm, therefore, the number is not used for statistics.
Fig. 6. Relationship between post-harvest soil water content [105-120 cm] and post-harvest soil nitrate-nitrogen (Nitrate-N) concentration at deep profile depths [90-180 cm] in forty soil profiles in two commercial winter wheat sites studied in 2018.

Table 1. Characteristics for the two commercial wheat sites sampled for crop rooting depth in fall 2018.

| Site    | Wheat Class‡ | Variety                  | Previous Crop | Tillage      |
|---------|--------------|--------------------------|---------------|--------------|
| Whitman | SWW          | Ovation, Puma, SY107     | Chickpea      | No Till      |
|         | mm           |                          |               | Fall Disc    |
| Latah   | HRW          | Jet, Touchstone          | Spring Wheat  |              |

† MAP, Mean annual precipitation; Whitman County MAP estimated from the ten-year average precipitation reported by AgWeatherNet (2018); Latah County MAP estimated from the Latah County soil survey (Barker, 1981).
‡ SWW, soft white winter wheat; HRW, hard red winter wheat

Table 2. Model fitting results for Eq. 1 showing the effect of soil bulk density at sampling depth (d), and soil water content on winter wheat root density† at two sites sampled in the fall of 2018.

| Parameter † | § | β ¶ | SE # |
|-------------|---|-----|-----|
| β₀          |   | 3.29 ** | 0.44 |
| r (cm)      |   | -0.02 ** | 6.51E-03 |
| post-harvest water content (g g⁻¹) |   | -3.75 ** | 0.96 |
| bulk density (g*cm⁻³) |   | -0.55 * | 0.31 |
| S           | Whitman | 0.26 * | 0.11 |
| Latah |   |   |   |
| r x bulk density (g*cm⁻²) |   | 5.11E-3 ns | 4.12E-03 |
| r x S (cm) | | Whitman | -2.56E-03 * | 1.52E-03 |
| Latah |   |   |   |

R²=0.74
** Significant at α=0.1, 0.01 level respectively.
† Root density was the average density of root intersections on the face of a core cross section measured in intersections per cm². Values are the average of 3 replicate measurements per depth per profile.
‡ r, profile depth of the bottom of the soil core (d= 15cm to 120cm at 15cm intervals); post-harvest water content, post-harvest water content of 15-cm soil core with bottom of core at depth d; S, site.
§ Underlined site was the reference group.
¶ Coefficient.
# Standard error.

Table 3. Model fitting results for Eq. 2 showing the likelihood of root restriction† at a particular depth as affected by soil bulk density at two sites sampled in the fall of 2018.

| Parameter‡ | β § | SE  | Odds Ratio | Confidence Interval |
|------------|-----|-----|------------|---------------------|
| β₀         | -7.96** | 2.22 | NA ¶ | NA NA |
| r (cm)     | 0.06**  | 0.01 | 1.07      | 1.04 1.10           |
| bulk density (g*cm⁻³) | 0.31* | 1.35 | 1.37 | 1.01 21.10 |
| S          |       |     |           | |
| Whitman    | -0.67 | 0.48 | 0.51      | 0.19 1.31           |
| Latah      |       |     |           | |
| Test       | df   | χ²  |           | |
| Likelihood Ratio | 1 | 54.20 | ** | |
| Test       |      |     |           | |
| Hosmer &   | 2    | 0.52 |           | |
| Lemeshow   |      |     |           | |

** Significant at α=0.1, 0.01 level respectively.
† Root restriction at a particular depth was a binary response variable that was 1 if a depth in the profile was the root restrictive depth. Root restrictive depth was defined as the depth in the profile at which root density was less than or equal to 0.25 intersections cm⁻². Root density was the average density of root intersections on the face of a core cross section measured in intersections per cm². Values are the average of 3 replicate measurements per depth per profile.
‡ r, profile depth of the bottom of the soil core (d= 15cm to 120cm at 15cm intervals); S, site (underlined site was the reference group).
§ Regression coefficient of binary logistic model.
¶ NA, does not apply.

Table 4. Relationship between post-harvest soil water content and grain yield, biomass yield, and harvest index for two commercial wheat sites sampled in fall 2018 in the Palouse agricultural region.

|                       | r    |   |
|-----------------------|------|---|
| Grain yield and Θ[105-120] cm | -0.51** |
| Biomass yield and Θ[105-120] cm | -0.28  |
| Harvest index and Θ[105-120] cm | -0.32  |
Grain protein concentration and $\Theta_{[105-120]\text{ cm}}$ -0.03

585 ** Significant at $\alpha=0.01$.
586 † $\Theta_{[105-120]\text{ cm}}$, post-harvest volumetric water content of soil cores collected from 105-120 cm depth in studied profiles; Harvest index, ratio of grain yield to total biomass and grain yield.
588 ‡ $r$, Pearson’s correlation coefficient.
Bulk density (g cm$^{-3}$)

Site

Latah

Whitman

157x117mm (300 x 300 DPI)
