Radish Cover Crop Growth and Compaction Alleviation Potential in Southeastern Coastal Plain Soils

by

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Abstract

Soil compaction in the form of hardpans often restricts cash crop root growth in the southeastern U.S., reducing plant vigor and yield potential for crops with deep taproots such as cotton (*Gossypium hirsutum*). Planting forage radish (*Raphanus sativus*) as a cover crop has been suggested as a method to alleviate hardpans and preserve soil structure by reducing the need for deep tillage. Research is needed to determine if forage radish can alleviate compaction in Coastal Plain soils and provide basic information on radish management to determine appropriate planting dates and cultivars for the Southeast. To address this objective, a field study using five radish cultivars (i.e., ‘Lunch’, ‘Sodbuster’, ‘Nitro’, ‘Tillage’, and ‘CCS779’) planted on three planting dates (i.e., mid-September, mid-October, and mid-November) at two locations in the Coastal Plain region of Alabama was created to evaluate radish growth and soil compaction alleviation in cotton. Plant canopy width and foliage, root, and total dry matter were measured at five sampling times during the growing season. Root diameter and root length aboveground, belowground, and in total were also measured. Plots were evaluated for soil compaction using a tractor-mounted penetrometer after cover crop termination, which revealed that radish cover crops did not reduce penetration resistance compared to fallow plots. No differences were observed between cultivars for most growth parameters. However, planting date had a significant effect on radish growth—earlier planted radishes consistently produced larger canopy widths, more dry matter, and larger roots. In this study, Sep-planted, Oct-planted, and Nov-planted radishes produced a maximum of 19,373, 3246, and 307 kg ha^{-1} of dry matter, respectively. Radish growth was markedly different between the 2017-18 and 2018-19 growing seasons, suggesting

that planting date and accumulated growing degree days are more important than cultivar selection for dry matter production and root growth.

To test the ability of radish roots to alleviate compaction, a greenhouse study was conducted to determine the ability of radish taproots to penetrate compacted topsoil in PVC cylinders. Two radish cultivars (i.e., 'Tillage' and 'Smart') were planted into 40 cm PVC cylinders with and without a constructed hardpan (>1.7 g cm^{-3}) located approximately 30 cm from the soil surface. Canopy width and aboveground root length data were collected weekly. Cylinders were opened after three months to observe root length (aboveground and belowground) and biomass for radishes in each cylinder. While no radish was able to penetrate into or through the hardpan, 'Tillage' radishes produced wider canopies and longer aboveground and total root lengths than 'Smart' radishes, while radishes grown in compacted cylinders produced more foliage and total dry matter than those grown in uncompacted cylinders. These results indicate that while radish cultivars may have marked growth patterns and morphological differences, there is little evidence that those differences may lead to greater penetration into compacted soil layers. Further research is needed to assess the bulk density at which radish taproot growth is restricted.

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I. Literature Review

Conservation Cropping Systems in the Southeast

The southeastern United States enjoys a unique geographic, geologic, and climatic location. A wide variety of crops can be grown in the Southeast due to the warm, humid climate and diverse soil types in the region. However, the same climate that supplies warm temperatures and high annual rainfall, paired with unsustainable agricultural practices, has led to an unprecedented amount of soil degradation. Trimble (1974) estimated that between 14 and 24 cm of soil has eroded from Piedmont uplands due to intensive cotton farming from 1820-1930, with additional erosion occurring since then. Soils under long-term conventional cultivation have significantly lower soil organic carbon (SOC) than those under conservation tillage or pastureland (Causarano et al., 2007) and often contain more readily erodible clay fractions (Shaw et al., 2002). To protect their soil resources, Alabama farmers have adopted farming practices that reduce erosion and restore soil quality in degraded soils. These include conservation and no-tillage practices. In 2017, 42% of the total cropland in Alabama was either under conservation (14.7%) or no-till (27.2%) operations, while only 9.2% was conventionally tilled (USDA National Agriculture Statistics Service, 2019). Alabama farmers have also begun to adopt cover cropping to further enhance soil benefits from minimal tillage. By 2017, cover crops were planted on 8.1% of the total cropland in Alabama, up from 7.2% in 2012 (USDA National Agriculture Statistics Service, 2019). According to a SARE survey, cover crop acreage by respondent is increasing each year, with an expected 451 acres per respondent planted in cover crops in 2017 (CTIC, 2017). This highlights the need for continued research on cover crops and cover crop management to meet producer demands.

Conservation Tillage Systems–Benefits and Challenges

Conservation tillage is operationally defined as “a tillage or tillage and planting combination that leaves a 30% or greater cover of crop residue on the surface” (Soil Science Society of America, 2008). One of the most immediate and beneficial results of a conservation tillage system is preservation of soil moisture by reduced evaporation from the soil surface (Blevins et al., 1971). Other benefits include the reduction of soil runoff and erosion (Langdale et al., 1979; Wuest et al., 2008) and reduced soil temperatures (Tollner et al., 1984). Long-term benefits include increases in SOC (Edwards et al., 1992; Beare et al., 1994) and increased infiltration rate (Azooz and Arshad, 1996). Franzluebbers (2010) estimated that in Alabama, the yearly SOC accumulation rate from switching from conventional tillage to no tillage could be as high as 0.66 Mg C ha^{-1} y^{-1}. However, several studies have shown that the net result is rather a redistribution and accumulation of SOC near the soil surface (Powlson and Jenkinson, 1981; Carter, 2005; Dolan et al., 2006). Other long-term benefits include improved aggregate stability (Wright et al., 1999) as well as increased microbial dry matter and mycorrhizal fungi diversity (Jansa et al., 2003; Feng et al., 2003; Mathew et al., 2012).

Despite the benefits, conservation tillage systems—primarily no-till systems—may also create unfavorable soil conditions that limit productivity. While there is no consensus on the effect of long-term no-till treatments on soil bulk density, penetration resistance, and porosity, several studies have shown those soil physical properties to be less favorable in no-till than conventionally-tilled soils (Hill, 1990; Mahboubi et al., 1993; Ismail et al., 1994; Jin et al., 2011). This often leads to an increase in root density in the upper 5 cm of the soil profile in conservation systems, while in conventional tillage systems, the crop root systems are more evenly distributed throughout the profile (Barber, 1971; Izumi et al., 2009). Subsoiling has been used in conjunction with conservation tillage systems to break up compacted soil layers and allow roots to penetrate deeper into the soil. One region where this technique has been useful is the Tennessee Valley region of Alabama, where cotton yields decreased after the adoption of no-till practices due to compaction in the fine-textured soils of the region (Raper et al., 1998, 2000a, 2000b). Siri-Prieto et al. (2009) showed that in-row subsoiling increased peanut yields by 1.5 Mg ha^{-1} compared to strict no-till. However, the transition to no-till alone—without supplementing practices—might not be the most sustainable model. When cover crops were not utilized, net returns for cotton in a no-till system decreased in a twenty-nine-year study of the economics of cover crops and tillage practices in Tennessee (Zhou et al., 2017).

Soil Compaction Issues in the Southeast

The effect of repeated passes over a field at high water contents (optimum water contents for compaction vary with texture), can lead to the formation of a root and water-limiting layer called a hardpan (Soil Science Society of America, 2008). This effect occurs irrespective of tillage treatment, although intensive tillage can compound the effect. According to Medvedev and Cybulko (1995), soil water content is the main variable influencing the bearing capacity of a soil. The State of Alabama receives one of the highest annual precipitation amounts (1400 mm) of any state in the United States (NOAA National Centers for Environmental information, 2018). Since high soil moisture can exacerbate compaction, it can be difficult for Alabama producers to time farming operations so that the compacting effects of running machinery are reduced, particularly in conservation systems. Further, management systems that promote increased soil moisture may also increase issues with compaction. Regarding machinery, wheel load (i.e., weight of machinery) has been shown to compact subsoil independently of topsoil, while ground pressure (i.e., wheel load divided by contact area) works to compact topsoil independently of subsoil (Smith and Dickson, 1990). As agricultural machinery gets heavier, it is essential to reduce the amount of land traversed by equipment. Using GPS to track machinery passes through fields, it was estimated that in conventional tillage operations, 87.5% of the field area was trafficked by tires at least once during a year. For minimum till it dropped to 72.8%, and for no-till it was 55.7% (Kroulík et al., 2009). In the UK, controlled traffic, or tramlines, have proven useful in reducing soil compaction by designating permanent strips for tire traffic in a field (Chamen et al., 2003).

With respect to soil texture, coarse-textured soils tend to experience compaction stress vertically in the profile, and fine-textured textured soils tend to experience compaction multidirectional throughout the profile (Ellies Sch et al., 2000). Gysi et al. (2001) found that a surface layer of sand significantly reduced the pressure beneath tires and may protect a soil from compaction. In Alabama, soil types vary from clay and silt loam surface textures in the Limestone Valley Region of north Alabama and the Blackbelt Region of central Alabama, to loamy sand textures of the Coastal Plain Region of south Alabama (Mitchell, 2008). This variation in soil type has led to a diversity of compaction issues throughout the State of Alabama. Dexter (1988) characterized soil structural degradation (i.e., compaction) as occurring in three different steps (independently or sequentially). First, intact aggregates are rearranged as to reduce porosity. Second, aggregates break apart and fill remaining pores. And third, at the critical moisture content (which would change with soil texture), aggregates will form a structureless mass.

While there are many field operations that may induce compaction via tire traffic, alleviating compaction only occurs once, via tillage or subsoiling. In some regions of the U.S., freeze/thaw cycles are important for compaction alleviation. However, those cycles do not frequently occur in the southeastern U.S. and can be largely disregarded. It has been shown that the higher soil strength and more defined aggregates formed under conservation tillage can increase the resiliency of a soil to stresses that would otherwise structurally degrade the same soils under conventional tillage (Wiermann et al., 2000). The study also found that although a hardpan was formed under each tillage system, the pan served to protect underlying soil from further structural degradation. With respect to depth, hardpans generally form immediately below the maximum depth of tillage, with no-till/no-subsoiling practices forming the shallowest pan, conventional tillage forming an intermediate pan, and subsoiling forming the deepest pan (Raper et al., 1998; Clark et al., 2003). However, hardpans can also form at other depths, and/or in conjunction with subsurface E horizons (Chen and Tessier, 1997; Serap Gorucu et al., 2003). Understanding the depth to hardpan can be useful for producers who can vary the depth of tillage/subsoiling which can significantly reduce fuel costs while maintaining yields (Raper et al., 2007). However, different crops may also necessitate different tillage treatments to maximize yields, so varying depth of tillage may only be feasible in certain cropping systems (Siri-Prieto et al., 2009; Balkcom et al., 2010). Winter grazing of cover crops is an option for producers looking to increase net returns but may also compact soils and reduce cash crop yields. Soil compaction by livestock can be very similar to that formed from machinery but compaction levels vary depending on animal weight and grazing intensity (Hamza and Anderson, 2005).

Hardpans, in addition to other morphological pans, are common features of many southeastern U.S. soils (McCracken and Weed, 1963; Kashirad et al., 1967). Since soil compaction shows no evident signs at the soil surface, farmers may misdiagnose its effects to another cause or misattribute poor crop growth to soil compaction (Hamza and Anderson, 2005). However, when it is present, compaction often results in significant yield loss. Sadras et al. (2005) found that reduced plant growth in compacted soils was related to the decreased ability of the plant to capture water and nutrients. The study also found that subsoiling to break apart the compacted zone resulted in increased wheat grain yields of up to 43%, often overcoming the cost of subsoiling. In cotton, a crop known to be susceptible to compaction, lint yield was reduced by 11.8 to 14.7% by the presence of a tillage pan in the Mississippi Delta (McConnell et al., 1989). In Spain, hardpans reduced leaf area index (26 and 12%), root length (40 and 33%), evapotranspiration (12 and 7%), and cotton seed yield (28 and 10%) (Coelho et al., 2000) over two years. Lowry et al. (1970), created artificial hardpans in plastic cylinders and found cotton seed yields to be 12 to 26% of the yield in uncompacted cylinders. They hypothesized that the main reason was a limited water supply due to the restricted rooting volume. In Ohio, soybeans exposed to 10 and 20 Mg axle loads yielded 9 and 14% less, respectfully, compared to a control treatment (Flowers and Lal, 1998). While compaction is a pressing issue for southeastern farmers and subsoiling is a common solution, it is quite expensive, with benefits that quickly disappear with recurring traffic (Raper and Bergtold, 2007). In addition to reducing the trafficked area of a field, another option is finding crops that may alleviate compaction without the need for heavy machinery.

Cover Crops—Perception, Benefits, and Challenges

Cover crops, by definition, serve to cover the soil surface and reduce soil degradation by water and wind erosion (Reicosky and Forcella, 1998). In Europe, the term of "catch crop" is often used to distinguish a cover crop's ability to scavenge and retain nutrients for subsequent crops (Struik and Bonciarelli, 1997). Irrespective of the terminology employed, these crops have increased in usage and popularity between farmers and agricultural scientists alike. According to the 2016-2017 SARE Cover Crop Survey of farmers using cover crops, 86% of respondents agreed or strongly agreed with the statement that cover crops resulted in improved soil health on their farm (CTIC, 2017). However, it should be noted that regarding questions on yield advantage, economic advantage, yield consistency, and input reduction in cover crop systems, roughly half of respondents were either neutral or disagreed with the statements. From farmer-reported data, yields were shown to increase with the use of cover crops, though the authors of the SARE survey indicated this could be due to selection bias (CTIC, 2017). This highlights the need for further research to evaluate effects of cover crops on farm productivity.

Reduction in soil loss is arguably the most immediate benefit observed for cover crops. In a conventional tillage system in the southern Coastal Plain, cover crops were able to reduce soil loss in a three year span by 92% (92.6 to 7.4 Mg ha^{-1}) (Martin and Cassel, 1992). Another sought-after benefit of cover crops is the contribution of nutrients to the subsequent crop. Legumes are a popular cover crop planted to provide N to the cash crop, and have the potential to boost yields and/or reduce N fertilizer requirements (Ebelhar et al., 1984; Decker et al., 1994). Serving as catch crops, non-legume cover crops uptake N proportionally to their dry matter production, possibly leading to greater pools of immobilized N than legume crops (Meisinger et al., 1991; Dabney et al., 2001). Cover crops can also reduce weed populations for the subsequent crop. Many contain allelopathic compounds that may biochemically inhibit weed seed germination (Weston, 1996). However, the main method of weed suppression by cover crops is simple competition. In studies by Bukart et al. (2003) and Teasdale and Daughtry (1993), “smother crops” significantly reduced weed pressure by reducing the amount and wavelength of light reaching the soil surface. The same study also found that hairy vetch (*Vicia villosa*) cover crops significantly reduced the daily maximum soil surface temperature as well as daily soil temperature fluctuations, while conserving soil moisture in droughty periods compared to bare soil. In summary, reduced erosion, nutrient supply, weed suppression, and moisture storage are some of the short-term benefits frequently observed with cover crops.

Other benefits of cover crops lie in their potential to sequester C. Carbon sequestration is widely recognized as a means to impact climate change by removing CO_2 from the atmosphere and accumulating it in the soil as SOC (Lal, 2004). Poeplau and Don (2015) estimated 0.12 Pg of C could be sequestered annually from the use of cover crops, enough to offset the amount of greenhouse gas emissions from agriculture. With declining SOC stocks inevitable under each climate scenario considered by Smith et al. (2007), SOC loss will be up to 44% less under the study’s “environmentally-minded” models, compared to "economically-minded" or "business as usual" models. While tillage system alone may not influence SOC stocks (Baker et al., 2007), greater SOC sequestration was found for cover crops in conservation tillage systems compared to conventional tillage systems (Olson et al., 2014).

While some benefits of cover crops are immediately realized, others may take years to be observed. Several studies help to shed light on the long-term effects of cover crops in agronomic systems. At Auburn University's Old Rotation, continuous cotton has been planted on a Typic Kanhapludult soil with and without winter legume green manure crops since 1896. Plots planted with winter cover crops have shown a statistically significant increase in total SOC (from 0.4% without to 0.9% with cover crops, in the top 15 cm) in addition to an increase in cotton lint yield (1180 kg ha^{-1} with cover crops and 460 kg ha^{-1} without, from 1996-2005) (Mitchell et al., 2008). It should be noted that cotton lint yields were not statistically significant until 1916, 20 years after the beginning of the experiment. A 12-yr study conducted in southern Illinois on a Typic Fragiudalf concluded that cover crops increased SOC stocks compared to no cover crop plots, irrespective of tillage treatment (Olson et al., 2014). In a 31-yr study conducted in Jackson, TN, cover crops were shown to increase microbial activities that cycle C and N in the soil, as well as increasing yield while reducing N inputs (Mbuthia et al., 2015). Basche et al. (2016) found that in a 13-yr experiment with an annual rye (*Secale cereale*) cover crop, soil water content at field capacity increased 10 to 11% and plant available water increased 21 to 22% compared to no cover crop. In a 25-yr experiment in the Mississippi River Basin, Patrick et al. (1957) found that vetch cover crops increased organic matter, soil N, water stable aggregates, noncapillary porosity, field capacity water content, and yield, while reducing bulk density, compared to no cover crop.

However, cover crops may not always produce benefits. In Jackson, TN, a 29-yr experiment was conducted to determine the effect of four cover crops and two tillage treatments on net returns for cotton production. The authors found that to maximize profits farmers should not plant cover crops—that they were not economically feasible without government subsidies at the time of the study (Zhou et al., 2017). A study by Olson et al. (2014) concluded that although 12 years of cover crops increased SOC stocks for each tillage treatment, the increase failed to produce significant yield differences for corn (*Zea mays*) and soybean (*Glycine max*) compared to no cover crop. After 13 years of planting winter annual cover crops under no-till in Maryland, physical properties (i.e., infiltration rate, water stable aggregates, hydraulic conductivity, etc.) were more positively affected in Coastal Plain soils than Piedmont soils, yet no differences between SOC or labile C were found between cover crops and no cover crop (Steele et al., 2012). Cover crops can deplete soil moisture for the cash crop if not terminated early enough or if there is inadequate precipitation before planting (Ebelhar et al., 1984; Unger and Vigil, 1998; Balkcom et al., 2015). If not managed properly, they can potentially serve as a host for arthropod pests (Dabney et al., 2001).

Forage Radish Cover Crop Overview

Elkins (1985) was one of the first scientists to propose using "plant roots as tillage tools," by using them to grow through compacted soil layers to maintain pore continuity into the subsoil. Tap-rooted dicot species that produce larger diameter roots have been correlated with greater penetration into compacted soil due to increased root growth pressure (Materechera et al., 1992). Termed "bio-drilling" by Cresswell and Kirkegaard (1995), this process begins with the creation of macropores in the subsoil by a tap-rooted "drilling" species and is followed by benefits of increased macroporosity to the next crop. Under this concept, rather than using crops known for increasing porosity such as perennial grass and tree species, an annual crop is used to accomplish in one growing season what might take years with other species. Fleshy, tap-rooted cover crop species have renewed interest in this concept.

Confusion can surround names applied to radishes that produce large, fleshy taproots. In their plant guide publication, NRCS lists terms such as "daikon," "forage," and "fodder" radish as alternative common names of oilseed radish (*Raphanus sativus* L.). They also list alternative scientific names as *Raphanus sativus* var. *oleifer* Stokes, *Raphanus sativus* L. *ssp*. Oleiferus, and *Raphanus sativus* L. var. *oleiformis* Pers. (Jacobs, 2012). While certain cultivar names are trademarked (e.g., 'Tillage'), the term "forage radish" has often been used in the literature to encompass all radishes of that type. This paper will also refer to them as forage radish.

Forage Radish and Compaction

Several studies have investigated the potential of forage radish to alleviate compaction by growing through compacted layers with its fleshy taproot. Chen and Weil (2010) found forage radish decreased penetration resistance more than rapeseed (*Brassica napus*, another tap-rooted Brassica species) or rye under three levels of induced compaction in a Mid-Atlantic Coastal Plain field. Furthermore, compaction levels had no significant effect on root or foliage dry matter of forage radish, with the number of radish roots increasing with increased soil strength (Chen and Weil, 2010). The number of roots did not increase with increasing soil strength for rye or rapeseed treatments. In a study containing the same treatments, forage radish increased soil air permeability as well as the least limiting water range (i.e., the range in soil water conditions that pose minimal impedance to crop growth) (Chen et al., 2014). However, these results were not observed for a coarse-textured soil included in the study. Kadžienė et al. (2011) also observed a positive impact of forage radish on soil macroporosity and gas diffusivity in a study comparing forage radish to a dyer's woad (*Isatis tinctoria*) cover crop on an Alfisol in Denmark. In Brazil, radish increased aggregate stability after 18 months compared to no-till or chisel-till (Guedes Filho et al., 2013). Forage radish was shown to penetrate and provide low-resistance root channels for a soybean crop in compacted Ultisols in Maryland. This effect, enhanced by drought, increased soybean yield in forage radish treatments as a monoculture or as a mixture with rye, compared to no cover crop treatments (Williams and Weil, 2004). However, Cresswell and Kirkegaard (1995) found that Brassica cover crops relied primarily on pre-existing root pores rather than creating their own, likely due to high soil strength. In Illinois, forage radish failed to affect physical soil or yield parameters in compacted, smectitic soils after one year, likely due to natural shrink/swell processes which occur in smectitic, high organic matter soils (Acuña and Villamil, 2014). Chen and Weil (2011) compared maize silage production following cover crops. Maize root numbers were greater for forage radish treatments compared to rapeseed and cereal rye cover crops under high levels of induced compaction. Although yield increased in cover crop plots compared to no cover crop, it was not statistically different. In Poland, forage radish improved porosity, increased wheat yield, and decreased bulk density in reduced tillage systems, often creating similar soil conditions to those in conventional tillage systems. These effects were not observed when forage radish was managed under conventional tillage (Głąb and Kulig, 2008). In a five-year study from Denmark, forage radish significantly reduced penetration resistance of a Typic Hapludalf soil in the plow pan region (32-38 cm) formed from years of moldboard plowing, irrespective of tillage treatment (Abdollahi and Munkholm, 2014).

Forage Radish Nutrient Uptake and Retention

While legumes may be regarded for their ability to fix and supply N to the next crop, forage radish can efficiently scavenge and cycle N to the rooting zone of the subsequent crop (Wahlström et al., 2015). This is important in cropping systems where nitrate leaching is an issue, e.g., sandy soils or when groundwater contamination is a concern. Kristensen and Thorup-Kristensen (2004) found crop rooting depth was a good indicator of nitrate N uptake. If N is recovered from deeper soil layers than the rooting depth of the subsequent crop, the result is a net input of N to the system which would otherwise be lost. In their study, forage radish roots were able to grow and uptake nitrate from >2 m and leave minimal nitrate in the soil compared to Italian ryegrass (*Lolium multiflorum*) and cereal rye. Similar results were observed by Wang and Weil (2018), who showed that forage radish could uptake N from topsoil and subsoil layers and concentrate it near the soil surface, even under a 168 kg N ha^{-1} fertilization rate. While variations in root growth account for N uptake from deep soil layers (50-100 cm), N present in the top 50 cm is subject to more transformational processes and is often weakly correlated to root growth parameters, making it harder to estimate (Thorup-Kristensen, 2001). Forage radish cover crops can be more efficient than winter cash crops (early or late-seeded) such as wheat at N uptake with the goal of reducing N leaching (Wahlström et al., 2015; Munkholm et al., 2017). Even after one growing season, radish and radish mixtures increased nitrate uptake levels compared to fallow (Acuña and Villamil, 2014).

Although forage radish does not accumulate the highest percentage of tissue N among cover crops, it can accumulate more N per hectare due to the combined root and foliage tissue N contents (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004; Jahanzad et al., 2017). Jahanzad et al. (2016) estimated that forage radish accumulated 96 and 43 kg N ha^{-1} with N concentrations of 27.9 and 18.2 g kg^{-1} in foliage and roots, respectively. This combined total is higher than or comparable to the estimated 119 and 39 kg N ha^{-1} accumulation or 38.5 and 16.1 g kg^{-1} concentration of winter pea (*Pisum sativum* subsp. *arvense* L.) and cereal rye, respectively. In North Dakota, Samarappuli et al. (2014) estimated forage radish N content (of only the above-ground dry matter) to be 76 kg ha^{-1}, less than forage pea (*Pisum sativum* L., 116 kg ha^{-1}), Austrian winter pea (85 kg ha^{-1}), and hairy vetch (87 kg ha^{-1}), but higher than forage turnip (*Brassica campestris* x *napus*, 69 kg ha^{-1}) or purple top turnip (*Brassica rapa*, 67 kg ha^{-1}).

Studies on forage radish to contribute N to subsequent crops are conflicting and may depend on whether radishes winterkill during the cover crop season, illustrating the need for further research. Radish cover crops either have no effect on subsequent crop yields (Vyn et al., 2000; Acuña and Villamil, 2014; Ruark et al., 2018), or in cases where they do, increased N availability was not the reason (Gieske et al., 2016). In other cases, forage radish increased N content of potato tubers and shoots, as well as N use efficiency while decreasing the N fertilizer requirement (Jahanzad et al., 2017). In sweet corn production, forage radish increased grain N content, but did not increase yields over levels of other cover crops, all of which likely supplied adequate N to maintain corn yield (Isse et al., 1999). A study from Lansing, MI showed that a radish cover crop significantly reduced nitrate N concentrations relative to no cover crop, but in turn, decreased N for the subsequent corn crop during critical growth stages. This served to decrease yields (by 3 and 12%) and profitability (\$129 to \$214 ha^{-1}) and increase yield response to N (63%) due to decreased N availability (Rutan and Steinke, 2019). The sooner a cash crop can be planted after radish termination (winter-kill or with herbicides), the greater chance it can benefit from N mineralization of the radish tissue (Jahanzad et al., 2016, 2017). An estimated 50 kg N ha^{-1} can be released from decomposing radish tissue during the winter, possibly leading to leaching losses (Van Eerd, 2018). Nutrients removed through dry matter leaching may also be significant—especially for P. Under simulated rainfall events, radish cover crops had higher runoff N and P concentrations than ryegrass or red clover (*Trifolium pratense*) (Miller et al., 1994). When left to decompose on the soil surface, forage radish lost 60% of its original N concentration after six weeks and up to 70% was lost when residue was buried. Nitrogen release was exponential in the first few weeks, with much more N lost than the other cover crops studied (i.e., winter pea and cereal rye) (Jahanzad et al., 2016).

Some studies report forage radish can cycle P and K to the soil surface. After three years, soil test P (via Mehlich-3 extraction) surrounding radish taproot holes increased due to decomposition of P-rich radish tissue and/or radish root exudates that increased available P (White and Weil, 2011). However, no increase in yield or corn tissue P was observed. The ability of radish crops to uptake large quantities of P could be exploited to either remove excess soil P or concentrate it in the rooting zone of low-P soils. Other studies have shown forage radish to be one of the most effective cover crops for P uptake, but not necessarily for increasing labile P (Soltangheisi et al., 2018). Forage radish not only accumulates significant P (12.8 kg ha^{-1}) but it can also accumulate high P levels in low rainfall years (Pavinato et al., 2017). Similar effects of increased K uptake and subsequent availability were observed after ten years of cover cropping in Denmark (Abdollahi and Munkholm, 2014). However, Isse et al. (1999) found forage radish had no effect on macronutrients (i.e., NH_4^+, P, or K) other than nitrate. Due to its low sensitivity to soil metals, forage radish may uptake significant—although insufficient—levels of Zn and Cu to aid in phytoremediation efforts (Vamerali et al., 2011).

Because of its high dry matter production, the sequestration potential of forage radish has been investigated as a potential atmospheric C sink. Mutegi et al. (2013) estimated that after 30 years, forage radish cover crops could store 4.9 t C ha^{-1} in the soil. It should be noted that the C sequestration model used in this study utilized climate data from Denmark, which is a drier, cooler climate than that of the southeastern U.S. The total amount sequestered was almost identical between tillage systems, although in no-till plots, ^{14}C-labeled radishes sequestered C at shallower depths than in conventional tillage. This input of C has also shown potential to offset C amounts removed from cereal straw for hay production and maintain SOC contents (Mutegi et al., 2011). Wang et al. (2017) observed that forage radish cover crops did not alter total organic carbon (TOC) in a two-year period, but significantly increased permanganate-oxidizable organic carbon (POXC, or active carbon) throughout the profile, with more POXC observed in radish plots after an N fertilizer application.

Forage Radish Growth and Dry Matter Production

Several ecosystem services—weed suppression, reduction in nitrate leaching, dry matter N content—are positively correlated to cover crop dry matter production (Finney et al., 2016). The ability of forage radish to produce high foliage and root dry matter makes it well-suited for cover crop systems where high dry matter is the target. However, dry matter production is largely limited to the fall in some climates because forage radish can winter-kill below temperatures of -4°C (Chen et al., 2014). Lawley et al. (2011) calculated forage radish dry matter in Maryland to range from 3900 to 6600 kg ha^{-1} for foliage and 1300 to 3200 kg ha^{-1} for roots. Combined, dry matter ranged from 5600 to 8400 kg ha^{-1}, out-yielding cereal rye when measured in the fall. Several other studies have also found forage radish dry matter yielding 2000 to 2190 kg ha^{-1} (Mutegi et al., 2011), 2252 kg ha^{-1} (Finney et al., 2016), 3960 kg ha^{-1} (Kristensen and Thorup-Kristensen, 2004), 5480 kg ha^{-1} (Jahanzad et al., 2016), 5600 kg ha^{-1} (Thorup-Kristensen, 2001), and 5830 kg ha^{-1} (Jahanzad et al., 2017).

In most of the above studies (conducted throughout the U.S. and Europe), forage radish produced the highest dry matter of the cover crops tested and out-yielded cereal rye, oat (*Avena sativa*), canola (*Brassica napus*), and a mix of the four (including forage radish) (Finney et al., 2016); winter rye (Thorup-Kristensen, 2001); winter pea and cereal rye (Jahanzad et al., 2016); winter rape, phacelia (*Phacelia tanacetifolia*), cereal rye, oats, Italian ryegrass, rye/vetch mix, and hairy vetch (Thorup-Kristensen, 2001); and cereal rye and winter pea (Jahanzad et al., 2017). When planted in different tillage systems, Mutegi et al. (2011) found that forage radish produced more dry matter and greater canopy cover in conventional tillage (2190 kg ha^{-1}) than no-till (2000 kg ha^{-1}).

Although forage radish has the ability to produce large amounts of dry matter, much of that dry matter is lost in a matter of weeks. This is due to the low C:N ratio of radish, which promotes net mineralization rather than immobilization of N (Ruark et al., 2018). Finney et al. (2016) found that a cover crop's C:N ratio is a better predictor of N supply and cash crop yield than dry matter in a study which compared cover crop monocultures and mixes that exhibited N-fixing and N-scavenging abilities with winter hardy and non-winter hardy species preceding a corn cash crop. Measured C:N ratios for radish foliage range from 9.02 to 16.0 (Ruark et al., 2018) to 12.1 to 12.5 (Mutegi et al., 2011); roots from 11.7 to 25.1 (Ruark et al., 2018) to 13.2 (Mutegi et al., 2011); and whole plants from 10.1 to 19.3 (Ruark et al., 2018) to 15.1 to 15.7 (Finney et al., 2016). Forage radish's low C:N ratio affects soil microbial communities by promoting bacterial degradation pathways, rather than fungal pathways observed in other cover crops (e.g., rapeseed and rye) (Gruver et al., 2010). Left on the surface, forage radish lost >50% of its dry matter after six weeks, this was increased to >70% in the same time period if the residue was incorporated. After 12 weeks, 25% of the dry matter from forage radish stabilized in the soil if left on the soil surface to decompose. If incorporated, only 10% stabilized after 12 weeks (Jahanzad et al., 2016).

Forage radish is often planted in a mixture of cover crops, which often dramatically affects its dry matter production. Murrell et al. (2017) found that brassica species often underperform in mixtures, compared to monocultures. Their study showed that when non-winter-hardy species (e.g., forage radish) are used in mixes, the total dry matter production in the spring is often reduced and N released from those crops can be utilized by other species in the mix, allowing them to dominate the mixture in the spring (e.g., rye). Ultimately, the productivity of the mixture did not exceed the productivity of the best performing species planted as a monoculture. Similar results have been observed when forage radish is over-seeded into cash crops. Sandler et al. (2015) observed less dry matter when forage radish was over-seeded into standing soybeans that had already produced a dense canopy, compared to years where the cover crop was planted earlier or drought decreased soybean canopy density. Finney et al. (2016) also found that if dry matter production is the objective, mixtures are unnecessary because they often yield less than component monocultures. Further, combining cover crops with complementary N functions (e.g., forage radish for N scavenging, and a legume for N-fixing) did not over-yield monocultures. Cover crop mixtures for other ecosystem services, such as compaction alleviation, have not been extensively studied, but a mixture of forage radish and rye for compaction alleviation and ground cover has been suggested (Chen and Weil, 2011).

Values for root:foliage dry matter ratio of forage radish are quite variable between studies, but can be high based on a study by Mutegi et al. (2011) in Denmark, where it was 0.7 in no-till plots, and 0.9 in conventional tillage plots. Lower ratios were measured by Chen and Weil (2010), who showed that compaction had no effect on radish root:whole plant dry matter ratio. With respect to rooting depth, Williams and Weil (2004) observed radish roots growing 10 to 15 cm deep before roots began to grow horizontally. Other studies have observed roots extending 15 to 30 cm into the soil, decomposing and leaving holes approximately 5 to 10 cm deep. This seems to indicate that while radish roots may extend deep into the soil, only a small portion of the total root (5-10 cm) affects the surrounding soil enough to leave noticeable holes (i.e., the fleshy portion of the root) (White and Weil, 2011). In some instances, roots would grow horizontally before reaching a pre-existing root channel and begin growing vertically again. Kristensen and Thorup-Kristensen (2004) planted forage radish on a Typic Agrudalf soil on August 8 and observed radish roots growing at a rate of 3.5 mm d^{-1} $°C^{-1}$, and reaching a depth of 1 m on September 20, after 626 d °C (accumulated daily temperature from sowing, calculated as the accumulation of heat units above 0°C using daily average temperatures). Roots reached a depth of 2.24 m by October 23. By that same date, Italian ryegrass had reached a depth of 0.64 m and cereal rye had reached 1.06 m. In another study by Thorup-Kristensen (2001), roots grew at a rate of 2.0 mm d^{-1} $°C^{-1}$, and reached a depth of 1 m after 750 d °C. It took the other cover crops in the study (winter rape, phacelia, rye, oats, ryegrass, vetch, rye/vetch mix, *Malva sylvestris*, and *Agrostemma githago*) 789 to 1375 d °C to reach 1 m. These studies highlight the ability of forage radish—when planted early—to quickly establish a deep root system before winter-killing.

Forage radish may also reduce spring weed pressure. In Germany, cover crops were planted and weed pressure was measured four, eight, and twelve weeks after planting. Forage radish was the only cover crop to suppress weeds in each experiment at eight weeks after planting, and was able to reduce weed density by 66% compared to control plots twelve weeks after planting (Brust et al., 2014). In Maryland, when planted before September 1, forage radish achieved canopy closure within 4 to 6 weeks and provided complete weed suppression into March. However, by the traditional time of subsequent corn planting and into the growing season, there was no residual weed suppression by the radish crop (Lawley et al., 2011). The authors concluded that if forage radish and the subsequent corn crop were planted early enough, the need for a pre-plant burndown herbicide application could be eliminated, provided that a post-emergent herbicide treatment was still used.

By using decomposing radish tissue, aqueous tissue extracts, and observing their effects on weed seed emergence, Lawley et al. (2012) demonstrated that the primary mechanism for weed suppression was fall weed competition—not allelopathy. Therefore, forage radish cover crops planted for weed suppression should be managed to produce maximum canopy growth and ground coverage. Similar results were obtained in the Netherlands by Kruidhof et al. (2008), who observed forage radish took the shortest time of any cover crop tested (oilseed rape, rye, Italian ryegrass, lupin [*Lupinus albus*], and lucerne [*Medicago sativa*]) to reach 50% soil coverage. In Pennsylvania, forage radish monocultures showed intermediate results in reducing weed seed production and weed dry matter, with cover crop mixtures that included forage radish reducing weed seed and dry matter compared to mixtures excluding forage radish (Baraibar et al., 2018). This study also showed that winter hardiness was not always necessary for spring weed suppression. Excluding forage radish from mixtures increased weed dry matter in a study by Holmes et al. (2017), while weed dry matter was reduced 45 to 100% in radish monocultures.

As the name suggests, forage radish can be used as a forage crop, however, if given the choice, cows prefer similar crops such as brassica rape and leafy turnips over forage radishes, likely due to high nitrate N contents that confer a bitter taste (Horadogoda, 2009). Compared to grain crops, forage radish had comparable crude protein, low neutral detergent fiber (NDF), and very high nitrate N contents (14.9 and 9.0

g kg^{-1} dry matter in fall and winter, respectively) (Fulkerson et al., 2008). Due to high nitrate accumulation, forage radish consumption by cattle may need to be limited to a small portion of their diet to prevent nitrate toxicity. While forage radish yielded higher crude protein amounts than oats, lentil (*Lens culinaris*), cowpea (*Vigna unguiculata*), and foxtail millet (*Setaria italica*), its low acid detergent fiber (ADF) and NDF concentrations may cause nutritional problems in dairy cows and should be planted with a cereal crop (Hansen et al., 2013). Further, bolting (indicating the switch from vegetative growth to reproductive growth) of forage radish lowered forage quality substantially. In New Zealand, forage radishes have been specifically bred for grazing (Stewart and Moorhead, 2004), however, it is unclear to what extent they resemble forage radish intended for use as a cover crop.

Forage radish also may alter the soil microbial community through allelochemicals released into the soil during degradation. Brassica crops are known for the production of glucosinolates, which degrade into potentially microbe-toxic, volatile isothiocyanates (Gardiner et al., 1999). Gruver et al. (2010) observed more bacterivore nematodes in forage radish compared to the control, likely due to the stimulation of bacterial degradation of radish tissue. The study also found that C:N ratio was likely the primary driver of cover crop effects on soil microbiology. Further, no “biofumigant” or allelopathic effects were observed on nematode populations from the forage radish cover crop. A study by Jones et al. (2006) demonstrated that Reniform nematodes (*Rotylenchulus reniformis*) could not reproduce on radish winter cover crops. Forage radish, like other Brassica crops, are a non-host to arbuscular mycorrhizal fungi (AMF), and did not show any effect on subsequent AMF populations in corn, compared to rye which greatly increased AMF colonization of corn roots (White and Weil, 2010). Similar results were obtained by another study measuring AMF colonization of cotton roots in Alabama (Ucar, 2019). However, the study by White and Weil (2010) also found that a mixture of forage radish and rye did not increase corn root AMF colonization, while a rye monoculture did.

Research Objective

The adoption of no-till practices in the Southeast has led to both challenges and benefits for traditional cash crop management. As soil compaction continues to impact crop yields for susceptible crops such as cotton, methods to alleviate compaction will be necessary to maintain yields. Certain cover crops have been introduced as an alternative to subsoiling which have taproots that can grow through compacted soil and create low-resistance paths for subsequent crop roots to follow. Among those, forage radish has been the most popular. Multiple studies in Maryland and Denmark have found forage radish to decrease penetration resistance in compacted soils. However, their effectiveness to reduce soil compaction in southeastern U.S. soils, in rotation with deep-rooted cotton crops is unclear. Likewise, forage radish dry matter production has been sufficiently documented, but region-specific data on dry matter production according to planting date and cultivar is missing. Studies in the southeastern Coastal Plain are also needed to allow Alabama producers to make an informed decision about planting forage radish as a cover crop. Thus, the objectives of this research are to provide Alabama-specific data on radish growth and development as a function of cultivar and planting date, and secondly, to determine the ability of a forage radish cover crop to penetrate a representative Alabama Coastal Plain compacted soil to alleviate the need for subsoiling.

II. Growth and Compaction Alleviation Potential of Forage Radish Cover Crops in Alabama

Abstract

Soil compaction in the form of hardpans often restricts cash crop root growth in the southeastern U.S., reducing plant vigor and yield potential for crops with deep taproots such as cotton (*Gossypium hirsutum*). Planting forage radish (*Raphanus sativus*) as a cover crop has been introduced as a method to alleviate hardpans and preserve soil structure by reducing the need for deep tillage. Research is needed to assess the effectiveness of forage radish to alleviate compaction in Coastal Plain soils and provide basic information on radish management to determine appropriate planting dates and cultivars for the Southeast. Five radish cultivars (i.e., ‘Lunch’, ‘Sodbuster’, ‘Nitro’, ‘Tillage’, and ‘CCS779’) were planted on three planting dates (i.e., mid-September, mid-October, and mid-November) at two locations in the Coastal Plain region of Alabama to test the effect of radish cultivar and planting date on radish growth characteristics, dry matter production, and soil compaction alleviation in cotton. Plant canopy width and foliage, root, and total dry matter were measured monthly during the growing season. Root diameter, aboveground root length, belowground root length, and total root length were also measured. Plots were evaluated for soil compaction using a tractor-mounted multi-probe penetrometer after cover crop termination, which revealed that radish cover crops did not significantly reduce penetration resistance compared to fallow plots. No differences were observed between cultivars for most growth parameters, however, planting dates were often significant—earlier planting dates consistently led to increased canopy width, dry matter production, and root length and width. In this study, Sep-planted, Oct-planted, and Nov-planted radishes produced a maximum of 19,373, 3246,

and 307 kg ha^{-1} of dry matter, respectively. Radish growth was markedly different between the 2017-18 and 2018-19 growing seasons, suggesting that the date of planting and accumulated growing degree days were more important than cultivar selection for dry matter production and root growth.

Introduction

Soils of the southeastern U.S. are generally characterized by low SOC levels and readily erodible clay fractions (Shaw et al., 2002; Causarano et al., 2007). Further, these soils are prone to compaction which can decrease yields of deep-rooted crops such as cotton (Raper et al., 2000a). Alleviating compaction via subsoiling is often expensive and benefits may disappear without repeated use (Raper and Bergtold, 2007). The idea of using "plant roots as tillage tools," first proposed by Elkins (1985) then later termed "bio-drilling" by Cresswell and Kirkegaard (1995), has been introduced as a way to address compaction issues without disrupting soil structure and pore continuity with tillage. Recently, forage radish cover crops were planted as a method to alleviate compaction, provide soil cover to reduce erosion and weed pressure, and produce and return large amounts of dry matter into the soil (Weil et al., 2009).

Multiple studies have investigated the potential of forage radish to alleviate compaction by growing through compacted soil layers with its fleshy taproot. Studies from the Mid-Atlantic Coastal Plain region found that forage radish was able to decrease penetration resistance and increase air permeability more than rapeseed (another tap-rooted Brassica species) or rye under three levels of induced compaction in a field (Chen and Weil, 2010; Chen et al., 2014). Low-resistance root channels can then be utilized by succeeding crops to access subsoil moisture and possibly increase yield in drought conditions (Williams and Weil, 2004). These root channels have even been observed extending into and through hardpans created by years of moldboard plowing (Abdollahi and Munkholm, 2014). The effect of radish cover crops on soil porosity and bulk density in reduced tillage systems can even be similar to those values in conventional tillage systems. However, when forage radish was managed under conventional tillage, no further change in porosity or bulk density was observed in a study by Głąb and Kulig (2008). Another study observed radish taproots growing through pre-existing root channels in high-strength soils rather than creating new root channels (Cresswell and Kirkegaard, 1995). Other evidence points to the positive effects of forage radish crops on soil properties may be more evident in fine-textured soils than coarse-textured soils (Chen et al., 2014).

With respect to rooting depth, Williams and Weil (2004) observed radish roots growing to a depth of 10 to 15 cm before roots began to grow horizontally. Other studies showed roots extending 15 to 30 cm into the soil, and after decomposing, leaving holes approximately 5 to 10 cm deep (White and Weil, 2011). In some instances, roots would grow horizontally before reaching a pre-existing root channel and begin growing vertically again. Kristensen and Thorup-Kristensen (2004) observed radish roots reaching a depth of 2.24 m after two and a half months of growth in a sandy loam soil. These studies highlight the ability of forage radish—when planted early—to quickly establish a deep root system before winter-killing.

Other studies have investigated the ability of forage radish to produce high levels of root and foliage dry matter. When returned to the soil, this dry matter can increase SOC stocks—a much-needed benefit in the southeastern U.S.. Mutegi et al. (2013) estimated that after 30 years, forage radish cover crops could sequester 4.9 t C ha^{-1} in the soil. Wang et al. (2017) observed that forage radish cover crops significantly increased permanganate-oxidizable organic carbon (POXC, or active carbon) throughout the soil profile. Another positive effect of high biomass production is the potential for fall and spring weed suppression. In Maryland, when planted before September 1, forage radish produced canopy closure within 4 to 6 weeks and provided complete weed suppression throughout the fall and into March, potentially replacing the need for a pre-plant burndown herbicide application (Lawley et al., 2011).

The ability of forage radish to produce high foliage and root dry matter makes it well-suited for cover crop systems where greater biomass is preferred. However, because forage radish have been observed to winter-kill below temperatures of -4°C, dry matter production is often limited to the fall months in many climates (Chen et al., 2014). Lawley et al. (2011) calculated total forage radish dry matter in Maryland from 5600 to 8400 kg ha^{-1} when planted in late August or early September, out-yielding cereal rye in the fall. Several other studies also found forage radish dry matter yielding between 2000 and 5830 kg ha^{-1} (Kristensen and Thorup-Kristensen, 2004; Mutegi et al., 2011; Jahanzad et al., 2017).

Radish biomass production has been sufficiently documented, but region-specific data on biomass production by planting date is missing. Research is needed in southeastern Coastal Plain soils to allow producers to make informed decisions about planting forage radish as a cover crop. Further, due to the lack of information associated with specific forage radish cultivars, it is unknown if there are any cultivar-specific differences in performance. Thus, the objectives of this research are to provide data on forage radish growth and development in the Southeast as a function of cultivar and planting date, and secondly, to determine the ability of a radish cover crop to alleviate compaction in Coastal Plain soils.

Materials and Methods

This experiment was conducted during 2017-2019 at the E.V. Smith Research Center (EVS) in Shorter, AL on a Compass (Coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults) loamy sand, 1 to 3% slopes, and at the Wiregrass Research and Extension Center (WREC) in Headland, AL on an Orangeburg (Fine-loamy, kaolinitic, thermic Typic Kandiudults) sandy loam, 0 to 2% slopes. Background soil test data for each location can be found in Table 1.1. Treatments consisted of five radish cultivars (i.e., 'Lunch', 'Sodbuster', 'Nitro', 'Tillage', and 'CCS779') and a winter fallow control planted on three planting dates (i.e., mid-September, mid-October, and mid-November). The experiment was arranged in split-plot randomized complete block design with planting dates as main plots and cultivars as subplots. There were three replications of each cultivar according to planting date. In the first year, plots were 3.7 m wide and 9.1 m long and consisted of four forage radish rows. In the second year, plots size increased to 3.7 m wide by 12.2 m long. Before cover crop planting, plots were prepared by conventionally tillage to provide a clean seed bed. Forage radish was planted at 6.7 kg ha^{-1} to a depth of 0.61 cm in 0.91 m rows by a 4-row cone planter, to simulate the row-spacing of the subsequent cotton crop. Due to the overlap from the first season's cotton harvest with the second year's first radish planting date, plots were relocated to adjacent fields for the second year, with the same plot layout. To aid in stand establishment, 44.8 kg ha^{-1} of 13-13-13 fertilizer was applied at planting at EVS and 33.6 kg ha^{-1} of N fertilizer was applied at planting at WREC. In April, radishes that did not winter-kill were chemically terminated. During the first year, the soil was strip-tilled (with a subsoiler) approximately 10 cm from the radish row (to prevent radish bolts from interfering with the planter) prior to planting cotton in 0.91 m rows. During the second year the soil was strip-tilled approximately 10 cm from the radish row without a subsoiler, to help observe differences in treatments with respect to penetration resistance.

Radish growth data were collected monthly, starting in October (one month after the earliest planting date). Specific planting and sampling dates can be found in Table 1.2. Radish canopy width and dry matter (root and foliage) data were collected throughout the growing season (October through February for the first year, and October through March the second year). Radish plant density, root length (above and below-ground), and root diameter data were collected less frequently throughout the growing season. Radish plant density was measured one month after each planting date while (i.e., aboveground, belowground, and total root length and root diameter) were collected in February of each year. Each growth parameter was measured for 10 randomly-selected plants per plot, with the exception of plant density which was measured four times per plot. Canopy width was measured by using a ruler to determine the maximum diameter of the radish foliage. Stand counts were determined by using a 0.25 m^2 square and counting the number of plants in the 0.5 m row-section. Ten plants were pulled from each plot and dried in an oven for a minimum of 48 h before being separated into roots or foliage and weighed to determine dry matter. Root length was measured when plants were sampled for dry matter measurements, the length of the root was measured from the top of the root to the point where it narrowed to less than 1 cm. Although roots extended deeper, this was the point they often broke off when pulled out of the ground. The above- and below-ground root lengths were determined likewise, using a line that developed on the radish (the root was white below the soil surface and green above it) as the dividing line. Root diameter was measured at the point of maximum thickness of the root.

After cotton planting, a five-probe tractor-mounted penetrometer was used to measure penetration resistance (PR). The probes measured PR in five cm increments to a depth of 50 cm in five positions: row middle (cotton row), 22.5 cm to the left and right of the center (one of which represented the radish row), and 45 cm to the left and right of the center probe (representing un-trafficked and trafficked row-middles). Soil moisture samples were taken at the same time as penetrometer measurements from each plot at depths of 0 to 15 and 15 to 30 cm to ensure penetrometer differences were an effect of treatment and not moisture.

Daily weather data (maximum temp, minimum temp, and precipitation) were collected from weather stations at both locations over the course of the study. Growing degree days (GDD) were calculated using the formula $GDD = [\frac{Tmax - Tmin}{2}] - 5$. The base temperature of 5°C was selected for its previous use with radish and other brassicaceous crops (Ackroyd, 2015).

Statistical Methods

All analyses were performed using the generalized linear mixed model procedure (PROC GLIMMIX) in SAS version 9.4 (SAS Institute, 2013). The effects of cultivar, planting date, location, year, and relevant interactions were all analyzed and treated as fixed effects unless otherwise noted. Replication was treated as a random effect. Analysis of canopy width, foliage dry matter, root dry matter, and total dry matter were separated by year and location due to significant year by location interactions. Analysis of belowground root length, aboveground root length, total root length, and root diameter were also separated by year and location to maintain uniformity in data representation.

Analyses were conducted for individual sampling dates and it should be noted that those comparisons were between radishes that had been growing for different lengths of time (due to different planting dates). However, these comparisons were made to illustrate radish growth and development similar to a production system, where radishes may be planted at different dates. This approach was validated by a repeated measures analysis (analyzing months after planting for each planting date) that showed similar trends in radish growth when compared to the analyses of individual sampling dates.

For the above root measurements (i.e., belowground root length, aboveground root length, total root length, and root diameter), analysis was restricted to Sep-planted and Oct-planted radishes, since Nov-planted radishes were <1 cm in diameter and considered negligible. Since one cm was the determined cutoff to denote the fleshy portion of the taproot, any radish root less than that diameter was not considered for consistency across planting dates. Penetrometer data were separated by year and location due to the experiment changing physical locations between year one and two (each experiment lasted >1 year). To analyze the effect of weather on forage radish growth and development, linear regressions were created using the regression procedure in SAS (PROC REG) to correlate GDD and precipitation to radish dry matter and canopy measurements, since those data were collected throughout the growing season. All analyses utilized Tukey's HSD test for significance using $\alpha=0.05$.

Results and Discussion

Growing Degree Day Effect on Radish Growth

Given that radishes only winterkilled in 2017, it is assumed that winterkilling occurred when temperatures dropped below -5°C in January at both locations (to -8.3 and -10.8°C at WREC and EVS, respectively, shown in Fig. 1.1). This supports previous research that found winterkilling of radishes occurring below -4°C (Chen et al., 2014).

Given that earlier planted radishes produced more dry matter than later planted radishes, GDD were hypothesized to be the primary cause for this discrepancy. As a result, GDD were thought to account for the decrease in dry matter production for Oct-planted radishes in 2018. A linear regression utilizing GDD, GDD^2, cumulative precipitation (CP), and CP^2 was created and produced good correlations with total dry matter (R^2=0.90), foliage dry matter (R^2=0.80), root dry matter (R^2=0.89), and canopy width (R^2=0.87). Only data collected before bolting or winterkilling of some radishes in Jan were utilized in creating the regressions because it is assumed that dry matter and canopy width variables were affected by those events to a greater extent than any additionally accumulated GDD.

Sep-planted radishes accumulated similar GDD in all site-years (Fig. 1.2). Likewise, they produced similar total dry matter until winterkilling in Jan and Feb in 2017 and bolting in Jan and Feb in 2018. Oct-planted radishes accumulated more GDD in 2017 at WREC and in the first 75 days of growth at EVS. This is likely responsible for the discrepancy in dry matter production in Oct-planted radishes between 2017 and 2018. Nov-planted radishes accumulated more GDD in 2018 at EVS and in 2017 in the first 50 days of growth at WREC. However, only Nov-planted radishes at WREC produced more total dry matter in 2017 than 2018 (there were no differences in dry matter production at EVS). Due to partial winterkilling events in 2017 and bolting of radishes in 2018, the data suggest that cumulative GDD within a critical period of radish growth is better correlated with radish dry matter production than cumulative GDD over the entire growing season. In this study, that period seemed to be between planting and the Dec sampling date, as evidenced by the high R^2 value for canopy and dry matter variables.

Stand Count

There were significant differences in stand count for planting date at WREC in 2017 and EVS and WREC in 2018 after separation by year and location (Table 1.3). Oct-planted radishes had lower plant densities than Sep-planted and Nov-planted radishes at WREC in 2017 and 2018 and Nov-planted radishes at EVS in 2018. In those three site years, Oct-planted radish stand counts ranged from 5.6 to 10.1 plants per 0.5 m row-section, while Sep-planted radishes ranged from 8.6 to 11.9 and Nov-planted radishes from 11.3 to 12.7. Cultivar effects on stand count were observed in 2018 where 'Tillage' and 'Nitro' radishes had greater plant densities than 'CCS779' radishes at EVS (a difference of three plants per 0.5 m row-section), and 'Nitro' radishes had higher stand counts than 'Tillage', 'Sodbuster', and 'CCS779' radishes at WREC (a difference of four plants per 0.5 m row-section). The differences in stand counts could be attributed to equipment error, as planting equipment used at both locations often had to be re-adjusted before each planting. However, it is more likely that climatic conditions such as temperature and soil moisture at each planting date were the cause of the differences among planting dates. Additionally, cultivar trends for dry matter production do not follow cultivar trends for stand counts, so it is unlikely that stand count affected any other measured variables such as dry matter production.

Canopy Width

Analysis of canopy width according to sampling date showed a significant effect of planting date ($P<0.0001$) for each site-year (Table 1.3). At EVS in 2017, Sep-planted and Oct-planted radishes produced wider maximum canopies than Nov-planted radishes across all sampling dates (Fig. 1.3). For all other site-years, canopy width increased in the order of Nov-planted<Oct-planted<Sep-planted radishes. Sep-planted radish canopies in those site-years ranged from 45.7 to 78.1 cm, between 1.1 and 3.6 times larger than Oct-planted radishes and between 3.2 and 11.1 times larger than Nov-planted radishes (Table 1.4). Greater canopy width for earlier-planted radishes is likely due to the accumulation of growing degree days (GDD) after planting; later-planted radishes were simply not as developed as earlier-planted radishes. Planting date and cultivar interacted to affect canopy width for the Mar sampling date at EVS in 2018 and for the Jan, Feb, and Mar sampling dates at WREC in 2018 (ANOVA data according to sampling date not shown). However, the only consistent differences between these sampling dates was at WREC in 2018 where Nov-planted 'Lunch' and 'Sodbuster' radishes produced wider canopies than 'CCS779' radishes (data not shown).

Radishes that can produce larger canopies will lead to faster ground cover which is imperative in conservations systems to reduce erosion (Wuest et al., 2008) and decrease weed pressure throughout the winter (Lawley et al., 2012). In all site-years, Nov-planted radishes produced canopy widths ranging between 6.9 and 19.5 cm before winterkilling or bolting (Table 1.4), much less than what would be expected to provide sufficient ground cover and potential weed suppression. Oct-planted radishes produced intermediate canopy widths in three site-years (between 20.5 and 54.8 cm). Sep-planted radishes produced the largest canopies in three site-years (between 45.7 and 78.1 cm) and were the only radishes to produce larger canopies during the second year of the study. There were further differences observed due to location. Sep-planted, Oct-planted, and Nov-planted radish canopies were between 1.6 and 2.5 times wider at WREC than EVS during both years of the study. Although this study did not measure time until canopy closure due to radish row spacing, these results agree with other studies conducted in the mid-Atlantic region (Lawley et al., 2011) and indicate that radishes planted by mid-Sep in central and south Alabama have a greater ability than Oct-planted and Nov-planted radishes to be successfully implemented into a conservation system with goals to reduce erosion and decrease weed pressure.

Foliage Dry Matter

Analysis of foliage dry matter for sampling date showed a significant effect of planting date ($P<0.0001$) for each site-year (Table 1.3). At EVS in 2017, Sep-planted radishes produced more foliage dry matter than Oct-planted radishes early in the season (Fig. 1.4). From the third sampling (i.e., Dec) date to the end of the radish growing season, both Sep-planted and Oct-planted radishes produced more foliage dry matter than Nov-planted radishes. At WREC in 2017, earlier planting dates resulted in radishes with greater foliage dry matter, with the exception of the last sampling date when Sep-planted and Oct-planted radishes produced more foliage dry matter than Nov-planted radishes but were not different from each other. At EVS and WREC in 2018 a similar trend emerged, where foliage dry matter increased with earlier planting dates (i.e., Sep>Oct>Nov) across all sampling dates. At WREC in 2018, planting date and cultivar interacted to affect foliage dry matter during the last sampling date, where ‘Sodbuster’ and ‘Lunch’ radishes produced more foliage dry matter than ‘CCS779’ radishes (ANOVA data according to sampling date not shown). However, differences between cultivars were not observed for any other site-year.

Benefits of greater foliage dry matter production are similar to benefits of increased canopy width. With more dry matter remaining on the soil surface, temperature fluctuations are often reduced, potentially leading to less evapotranspiration and increased soil moisture (Teasdale and Daughtry, 1993). Further, increased residue left at the soil surface is necessary to increase SOC (Balkcom et al., 2013; Olson et al., 2014). During both years, foliage dry matter for Sep-planted radishes ranged from 27.3 to 450.3 g per 10 plants, between 1.2 and 11.5 times more foliage dry matter than Oct-planted radishes and between 24.2 and 96.6 times more foliage dry matter than Nov-planted radishes. With respect to location, radishes planted at WREC produced between 3.6 and 7.6 times more foliage dry matter than those planted at EVS during both years. Although 2018 provided a longer growing season for radishes, Oct-planted radishes still produced less foliage dry matter in 2018 compared to 2017 at each location.

These data show that planting radishes by mid-Sep led to consistently high foliage dry matter production (>115 g per 10 plants in three site-years), planting by mid-Oct led to low to intermediate levels of dry matter production and delaying planting until mid-Nov led to negligible (<9.2 g per 10 plants) foliage dry matter production (Table 1.4). It should be noted that dry matter production between years was comparable for Sep-planted radishes until the Jan and Feb sampling dates, when radishes began to bolt in

2018 but winter-killed in 2017. Although not conducted on the same climate or time-scale as this study, Villalobos and Brummer (2015) also found that delaying planting from mid-Jul to mid-Aug reduced foliage dry matter of forage radish by 58% in the southwestern U.S.

Root Dry Matter

Analysis of root dry matter production across sampling dates showed a significant effect of planting date ($P<0.0001$) for each site-year (Table 1.3). At EVS in 2017, earlier planting dates led to an increase in root dry matter (i.e., Sep>Oct>Nov) during the first two sampling dates (Fig. 1.5). Later in the growing season, Sep-planted and Oct-planted radishes produced increased root dry matter compared to Nov-planted radishes. At WREC in 2017, earlier planting dates resulted in increased root dry matter until the last sampling date, when Sep-planted and Oct-planted radishes produced more root dry matter than Nov-planted radishes. In 2018, earlier planting dates consistently resulted in greater root dry matter at EVS and WREC. At WREC in 2018, planting date and cultivar interacted to affect radish root growth during the last sampling date, where 'Lunch' radishes produced more root dry matter than 'CCS779' radishes (ANOVA data according to sampling date not shown). However, cultivar differences were not observed for any other site-year.

Largely cited as the most beneficial aspect of forage radishes is their ability to produce large, fleshy taproots, which aid in nutrient cycling (Kristensen and Thorup-Kristensen, 2004) and compaction alleviation (Chen and Weil, 2010). During both years of this study, root dry matter for Sep-planted radishes ranged from 55.7 to 421.6 g per 10 plants, between 1.9 and 41.7 times more root dry matter than Oct-planted radishes and between 72.3 and 234.2 times more root dry matter than Nov-planted radishes (Table 1.4). Radishes planted at WREC produced between 1.5 and 7.2 times more root dry matter than radishes planted at EVS. These data follow the same pattern as foliage dry matter, where Sep-planted radishes consistently produced the greatest dry matter, Oct-planted radishes produced low to intermediate dry matter, and Nov-planted radishes produced negligible dry matter.

Total Dry Matter

Analysis of total dry matter according to sampling date showed a significant effect of planting date ($P<0.0001$) for each site year (Table 1.3). Similar to results for foliage and root dry matter, early planting dates often resulted in increased total dry matter production (i.e., Sep>Oct>Nov). At EVS in 2017, Sep-planted radishes produced more total dry matter than Oct-planted radishes at the first sampling date. However, for the remainder of the growing season, both Sep-planted and Oct-planted radishes produced more total dry matter than Nov-planted radishes (Fig. 1.6). At WREC in 2017, earlier planting dates resulted in more total dry matter until the last sampling date, when Sep-planted and Oct-planted radishes produced more total dry matter than Nov-planted radishes. At EVS and WREC in 2018, earlier-planted radishes consistently produced more total dry matter than later-planted radishes over the entire growing season.

With many ecosystem services such as weed suppression, reduction in nitrate leaching, N contributions, and SOC contributions positively correlated to cover crop dry matter production (Balkcom et al., 2013; Finney et al., 2016), it is the goal of many conservation systems to maximize total dry matter production. Results from this study show that greater potential for dry matter accumulation is achieved with earlier planting dates.

Although foliage:root dry matter ratios varied in this study, there was a general trend that as the growing season progressed, the ratio decreased until the Jan sampling date, after which, bolting likely caused the ratio to increase again. In 2018—used because of more complete growth data—Sep-planted radish foliage:root dry matter ratios decreased from 10.6 and 10.3 for the Oct sampling date at EVS and WREC, respectively, to 0.5 and 0.4 at the Jan sampling date, and increased to 1.9 to 1.6 at the Mar sampling date. Ratios for Oct-planted radishes decreased from 12.6 and 11.5 for the Oct sampling date at EVS and WREC, respectively, to 1.0 and 2.1 at the Jan sampling date, and increased to 2.2 to 4.3 at the Mar sampling date. Ratios for Nov-planted radishes decreased from 6.3 and 6.7 for the Nov sampling date at EVS and WREC, respectively, to 3.0 and 4.5 at the Jan sampling date, and increased to 4.5 to 5.1 at the Mar sampling date. Additional trends show increasing foliage:root dry matter ratios with later planting dates for the last sampling month of all site-years. These data support other aspects of this study which show earlier-planted radishes producing more root dry matter than later-planted radishes.

Stand count data was used to calculate total dry matter production per hectare for each site-year. In 2017, Sep-planted radishes produced a maximum of 2334 and 8320 kg ha^{-1} of total dry matter at EVS and WREC, respectively, while Oct-planted radishes produced 1350 and 3246 kg ha^{-1}, and Nov-planted radishes produced 47 and 38 kg ha^{-1}. In 2018, Sep-planted radishes produced 3415 and 19,373 kg ha^{-1} at EVS and WREC, respectively, while Oct-planted radishes produced 220 and 1089 kg ha^{-1}, and Nov-planted radishes produced 38 and 307 kg ha^{-1}. Although total dry matter production was widely variable between years and locations, Sep-planted radishes yielded comparable or above many other published studies (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004; Mutegi et al., 2011; Jahanzad et al., 2016, 2017; Finney et al., 2016) in all site-years. Two site years (i.e., WREC 2017 and 2018) yielded dry matter exceeding 8000 and 19,000 kg ha^{-1}, higher than most other published values. This could be due to the coarse-textured soils and typically warm fall temperatures of the region. Oct-planted radishes only produced comparable dry matter to other published studies in one site-year (i.e., WREC 2017), while Nov-planted radishes produced negligible total dry matter across all site-years.

Penetration Resistance

Discussion of penetration resistance (PR) will be restricted to the second year of the study because of subsoiling of all plots during the first year. There were no significant effects of radish planting date or cultivar on PR when measured at five locations (-45, -22.5, 0, 22.5, and 45 cm) relative to the cotton row. During 2018, PR was numerically less for Sep-planted radishes compared to Oct-planted and Nov-planted radishes at all penetrometer probe locations (Fig. 1.7). At EVS in the 2018 growing season, all three planting dates produced numerically lower PR at the 22.5 cm probe distance than the center probe location (cotton row), across all plots. At WREC, although the center probe for all three planting dates consistently yielded the lowest PR—likely due to strip-tillage at planting—the -22.5 cm distance (closest to the previous radish row) for all planting dates yielded the next lowest PR. However, these differences were not statistically significant. Analysis of soil moisture did not show any differences between the 0 to 15 cm or 15 to 30 cm depths for any plots at either location, although the two depths were significantly different from one another for all site-years, so it is unlikely that moisture affected PR measurements within those depth classes.

Although these results do not agree with previous studies that have shown forage radish cover crops reducing PR in compacted soils (Chen and Weil, 2010; Abdollahi and Munkholm, 2014) the reason may be due to penetrometer probe placement. After radish termination, cotton was planted next to the radish row, and penetrometer measurements were taken in the cotton row and ± 22.5 cm away. This distance may not have placed a probe directly in the radish row. Therefore, changes in PR following radish growth may not have been detected. Further, in 2017, all plots were subsoiled during cotton planting, decreasing the likelihood of detecting a difference in PR due to radish root growth. Conversely, some studies have shown that forage radish crops do not increase porosity in coarse textured soils (such as the two soils used in this experiment) compared to fine-textured soils (Chen et al., 2014) and when conventional tillage is also practiced (Głąb and Kulig, 2008) (strip-tillage was utilized in this experiment). These results indicate forage radishes produced numerical differences in soil strength during 2018, however, possibly due to probe placement or experimental constraints that required relocating, these differences were not significant. Further research is needed to assess whether additional years in radish cover crops could lead to detectible differences in PR. To increase measurement precision, placing cotton directly in the radish row or physically marking radish row before winterkilling could be utilized in future experiments.

Root Variables

Given that Nov-planted radishes produced negligible roots (<1 cm in diameter) in both years, only Sep-planted and Oct-planted radishes were included in statistical analyses. In 2017, planting date affected measured root variables only at EVS (Table 1.3), where Sep-planted radishes produced more aboveground root length and larger root diameters than Oct-planted radishes. At WREC in 2017, there were no differences according to planting date between Sep-planted and Oct-planted radishes. At both locations in 2018, planting date affected all measured root variables after separation by year and location. Sep-planted radishes produced more aboveground root length, more belowground root length, longer total roots, and larger root diameters than Oct-planted radishes (Table 1.5).

Few cultivar effects on root variables were observed. At WREC in 2018, ‘Nitro’, ‘Sodbuster’, and ‘CCS779’ had longer aboveground and total root growth than ‘Tillage’ radishes. The differences between cultivars at WREC in 2018 for aboveground and total root length were 1.7 and 3 cm, respectively, while the differences between planting dates for the same site-year were 11 and 30 cm. Planting date and cultivar interacted to influence belowground root length and root diameter at WREC in 2018; Oct-planted ‘CCS779’, ‘Sodbuster’, and ‘Nitro’ radishes produced more belowground root growth and larger root diameters than ‘Tillage’ radishes. The only cultivar effect in 2017 was seen at WREC, where ‘CCS779’ radishes produced more belowground root length than ‘Sodbuster’ radishes (a difference of 1.3 cm). Given that cultivar effects were largely seen in only one site-year and were often much smaller than the effect of planting date, these data were not sufficient to indicate any meaningful differences between cultivars. However, the site-year in which most of the cultivar effects were seen was also the site-year that produced the largest dry matter (i.e., WREC 2018). It is possible that radishes did not grow large enough to express any varietal differences in the three other site-years. These results indicate that radish root growth was not dependent on cultivar compared to planting date.

Belowground root length is potentially the most important radish root variable with respect to compaction alleviation. However, the belowground root lengths reported represent the fleshy portion of the taproot (defined as >1 cm in diameter) and not the total length that radish roots may have extended into the soil. In 2017, Sep-planted and Oct-planted radishes extended 7.9 and 7.3 cm into the ground at EVS and 10.1 and 10.6 cm at WREC (Table 1.5). In 2018, Sep-planted and Oct-planted radishes extended 13.0 and 4.1 cm into the soil at EVS and 20.6 and 3.8 cm at WREC. These results agree with previous studies that showed the ability of early-planted radishes to establish deep taproots (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004). In our study, it was hypothesized that radish taproots extended to a constant soil depth after the first year due to the presence of a hardpan at each location. Figure 1.8 illustrates penetration resistance with depth for each site-year, to aid in diagnosing hardpans. At EVS, there was an increase in PR from 20 to 30 cm. At WREC during the first year there was possibly two hardpans (one from 15 to 20 cm then another from 35 to 40 cm), while during the second year there was only a significant PR increase at the 35+ depth. While radish roots did not extend to those depths in every site year, there is a trend that the fleshy taproots did not extend into zones of increased PR (e.g., PR values reached 4 to 6 MPa at EVS at depths below 15 cm). This result warrants further investigation. While 2017 was a favorable year of growth for Oct-planted radishes, 2018 led to a severe decline in belowground root length. This result highlights the variability of radish growth when delaying planting until mid-Oct. It should be noted that radishes sampled were often (but not always) observed growing horizontally once the root tapered to <1 cm, similar to results found by Williams and Weil (2004).

Radish roots extended aboveground in each year of the study. This aspect of radish growth is given little attention in most published literature (radish taproots are anecdotally noted in Weil and Kremen (2007) as being mostly aboveground). However, considering the frequency of this observation and potential for aboveground root growth to interfere with subsequent planting equipment, measurements for aboveground root length were included in this study. In 2017, Sep-planted and Oct-planted radishes extended out of the soil 4.2 and 2.8 cm at EVS and 5.3 and 4.7 cm at WREC, respectively (Table 1.5). In 2018, Sep-planted and Oct-planted radishes extended out of the soil 4.7 and 0.6 cm at EVS and 9.7 and 0.5 cm at WREC. Poor radish growth observed in Oct-planted radishes in 2018 is likely related to the low aboveground root lengths observed. Although these average values do not represent the wide range of values for aboveground root length (<1 to 14 cm) observed in the field, they illustrate that longer total root lengths do not necessarily indicate that a root grew deeper into the soil. Because values for aboveground root length decreased with later planting dates (and belowground root lengths also changed accordingly with planting date), it is hypothesized that aboveground root length is a function of radish root size rather than soil conditions such as the presence of a hardpan.

Total root length represents the sum of above and belowground portions of the fleshy taproot. Few studies have discussed total root lengths with respect to the fleshy portion of the taproot, and instead report the depth of the deepest root usually measured with minirhizotrons (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004). In 2017, Sep-planted and Oct-planted radishes produced roots totaling 12.1 and 10.1 cm at EVS and 15.5 and 15.3 cm at WREC (Table 1.5). In 2018, Sep-planted and Oct-planted radishes produced roots totaling 17.8 and 4.7 cm EVS and 30.3 and 4.3 cm at WREC.

Root diameter, not often cited in published literature, further represents the ability of radish roots to impact soil properties immediately surrounding the root. Sep-planted radishes produced larger root diameters than Oct-planted radishes (1.2 to 4.4 cm wider) for all site-years with the exception of WREC in 2017. Similar to other root parameters, Nov-planted radishes produced a negligible (<1 cm) root diameter. In 2017, Sep-planted and Oct-planted radishes produced roots 3.5 and 2.3 cm in diameter at EVS and 3.6 (for both planting dates) at WREC (Table 1.5). In 2018, Sep-planted and Oct-planted radishes produced roots 4.0 and 1.0 cm in diameter EVS and 5.3 and 0.9 cm at WREC.

Conclusion

This study illustrates the necessity of early planting dates for forage radish cover crops in the southern Coastal Plain. For canopy width and dry matter variables (i.e., foliage, root, and total dry matter), earlier planting dates consistently led to greater growth, in the order of Sep-planted>Oct-planted>Nov-planted radishes. For example, Sep-planted radishes produced 1.7 to 17.8 times more total maximum dry matter than Oct-planted radishes and 49.6 to 218.9 times more total maximum dry matter than Nov-planted radishes over the course of this study. Oct-planted radishes occasionally produced comparable growth to Sep-planted radishes (e.g., EVS 2017), however, this was an inconsistent trend. For root variables (i.e., aboveground, belowground, and total root length and root diameter), earlier planting dates resulted in more growth in the second year of the study, likely due to larger radishes at both locations. Growth in the second year of the study was much greater for Sep-planted radishes and much less for Oct-planted radishes. This was likely due to precipitation and increased GDD in the period between planting and bolting. Radish growth was also greater at WREC, located in south Alabama, than EVS, located in central Alabama. This is likely due to increased GDD and precipitation.

With respect to cultivar selection, there were very few cultivar effects observed in this study. Only one site year (i.e., WREC 2018) produced consistent cultivar trends with regard to root variables (i.e., aboveground, belowground, and total root length and root diameter). This occurred when root growth was the greatest, suggesting varietal differences may not be observed until high biomass production is achieved. This warrants further investigation under more controlled conditions than existed in this field study.

When cultivar effects were observed, differences in growth were often much greater between planting dates than between cultivars. These differences are not likely enough for a producer to consider selecting a specific cultivar. Due to the inconsistent nature of these results, there is little evidence that planting specific cultivars will lead to significant differences in growth.

This study confirmed other studies that showed radish cover crops winterkilling below -5° C, which was observed in the first year of the study but not in the second. Although no statistical differences were observed in PR, trends that earlier-planted radishes produced numerically lower PR values warrants further investigation. Due to the potential of forage radish to produce very high dry matter, canopy width, and large roots when planted by mid-Sep, this crop is well-suited for use in a cover crop rotation where weed suppression and dry matter production are desired. However, these data do not suggest that compaction alleviation should be a goal when planting a radish cover crop. Alternatively, producers should be encouraged to plant radish cover crops early to maximize cover crop benefits. Producers should consider that planting radish cover crops by Oct produced variable growth, and high biomass levels may not be achieved when planting in Oct. Planting in Nov produced negligible growth in all site-years, and therefore, producers are discouraged from late planting of radishes in the southern Coastal Plain. Thus far, cultivar selection has not produced noticeable differences in growth. Further research should focus on using GDD, precipitation, and soil type to predict radish growth to help determine optimal growing conditions and regions.

Table 1.1. Background soil test data for soil from E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL.

	pH†	P‡	K‡	Ca‡	Mg‡	CEC
Location		-----------------mg kg^{-1}	-----------------			$cmol_+ kg^{-1}$
EVS	6.4	50	78	112	733	2.5
WREC	6.4	49	65	75	581	2.4

†: Measured in a 1:1 soil to H_2O solution
‡: Extracted using Mehlich 1

Table 1.2. Planting and and sampling dates of forage radishes at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

	Planting Dates	Sampling Dates	Planting Dates	Sampling Dates
Location	--------------2017--------------		--------------2018--------------	
EVS	21-Sep	17-Oct	19-Sep	15-Oct
	19-Oct	15-Nov	17-Oct	19-Nov
	30-Nov	18-Dec	20-Nov	18-Dec
		12-Jan		15-Jan
		16-Feb		18-Feb
				13-Mar
WREC	22-Sep	13-Oct	17-Sep	15-Oct
	15-Oct	13-Nov	23-Oct	19-Nov
	15-Nov	19-Dec	19-Nov	18-Dec
		15-Jan		15-Jan
		18-Feb		19-Feb
				13-Mar

Table 1.3. Summary of analysis of variance (ANOVA) for canopy width, foliage dry matter (DM), root DM, total DM, aboveground root length, belowground root length, total root length, root diameter, and stand count in response to cultivar, planting date, and their interaction measured at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

	ANOVA, Pr > F								
	Canopy Width (cm)	Foliage DM (g per 10 plants)	Root DM (g per 10 plants)	Total DM (g per 10 plants)	Above-Ground Root Length (cm)	Below-Ground Root Length (cm)	Total Root Length (cm)	Root Diameter (cm)	Stand Count (plants per 0.5 m row-section)
	EVS 2017								
Planting Date (PD)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.5890	0.1072	0.0021	0.2379
Cultivar (C)	0.0345	0.5852	0.9381	0.8362	0.2565	0.0718	0.1176	0.3335	0.0602
PD x C	0.8721	0.9956	0.9998	0.9974	0.1028	0.4649	0.2070	0.1018	0.1063
	WREC 2017								
Planting Date (PD)	<0.0001	<0.0001	<0.0001	<0.0001	0.4024	0.2309	0.8712	0.8448	0.0033
Cultivar (C)	0.9887	0.9996	0.9647	0.9995	0.9469	0.0344	0.5324	0.7894	0.2565
PD x C	1.0000	0.9916	0.9285	0.9826	0.6214	0.6703	0.6585	0.5907	0.6591
	EVS 2018								
Planting Date (PD)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0165	0.0114	0.0128	0.0066
Cultivar (C)	0.0470	0.1909	0.7063	0.3421	0.4041	0.5848	0.5038	0.3740	0.0016
PD x C	0.9201	0.3483	0.9377	0.5432	0.4332	0.2187	0.2825	0.2425	0.1396
	WREC 2018								
Planting Date (PD)	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	0.0004	0.0003	0.0002	0.0031
Cultivar (C)	0.9834	0.9561	0.9913	0.9726	0.0054	0.0098	0.0056	0.0013	0.0011
PD x C	0.7404	0.9706	0.9990	0.9883	0.8494	0.0530	0.1218	0.0366	0.0558

Table 1.4. Forage radish maximum canopy width, maximum foliage dry matter, maximum root dry matter, and maximum total dry matter measured at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

Planting Date	Maximum Canopy Width (cm)	Maximum Foliage Dry Matter (g per 10 plants)	Maximum Root Dry Matter (g per 10 plants)	Maximum Total Dry Matter (g per 10 plants)
		EVS 2017		
Sep	33.9	27.3	55.7	83.5
Oct	33.3	21.9	29.6	51.4
Nov	8.5	1.1	0.4	1.5
		WREC 2017		
Sep	62.1	148.9	188.0	338.9
Oct	54.8	84.3	80.5	166.3
Nov	19.5	9.2	2.6	11.9
		EVS 2018		
Sep	45.7	115.9	92.0	181.1
Oct	20.5	10.8	6.9	17.9
Nov	6.9	1.2	0.3	1.5
		WREC 2018		
Sep	78.1	450.3	421.6	742.6
Oct	27.6	39.2	10.1	49.2
Nov	15.4	9.1	1.8	11.0

Table 1.5. Forage radish aboveground root length, belowground root length, total root length, and root diameter measured in Feb of each year at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

Planting Date	Aboveground Root Length (cm)	Belowground Root Length (cm)	Total Root Length (cm)	Root Diameter (cm)
		EVS 2017		
Sep	4.2 a	7.9 a	12.1 a	3.5 a
Oct	2.8 b	7.3 a	10.1 a	2.3 b
		WREC 2017		
Sep	5.3 a	10.1 a	15.5 a	3.6 a
Oct	4.7 a	10.6 a	15.3 a	3.6 a
		EVS 2018		
Sep	4.7 a	13 a	17.8 a	4.0 a
Oct	0.6 b	4.1 b	4.7 b	1.0 b
		WREC 2018		
Sep	9.7 a	20.6 a	30.3 a	5.3 a
Oct	0.5 b	3.8 b	4.3 b	0.9 b

† Different letters denote significance between planting dates within a site-year at $\alpha = 0.05$. Alternatively, means followed by the same letter do not differ within a site-year at $\alpha = 0.05$.

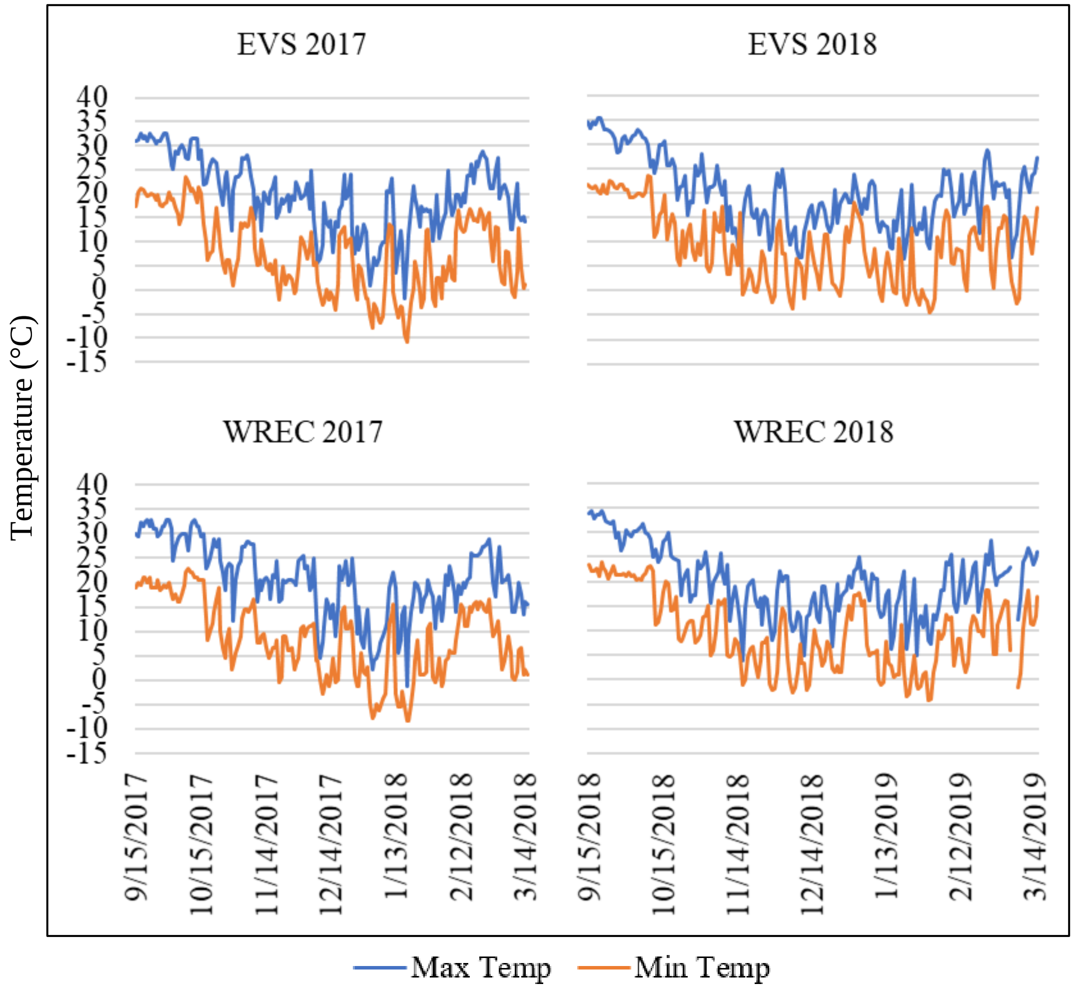

Figure 1.1. Maximum and minimum daily temperatures measured at E.V. Smith Research Center (EVS) Field Crops Unit in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

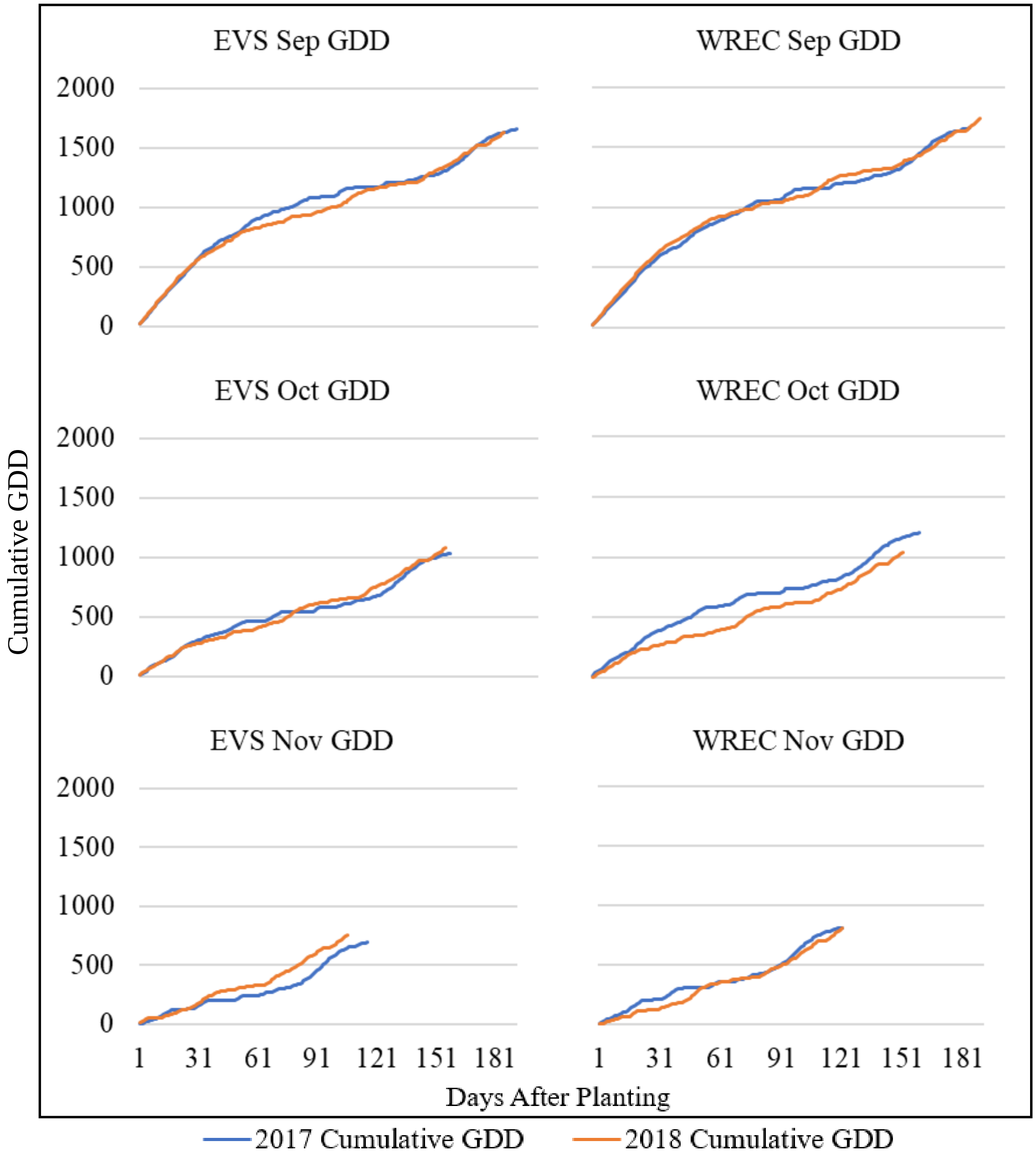

Figure 1.2. Cumulative growing degree days (GDD) for Sep-planted, Oct-planted, and Nov-planted radishes measured at E.V. Smith Research Center (EVS) Field Crops Unit in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

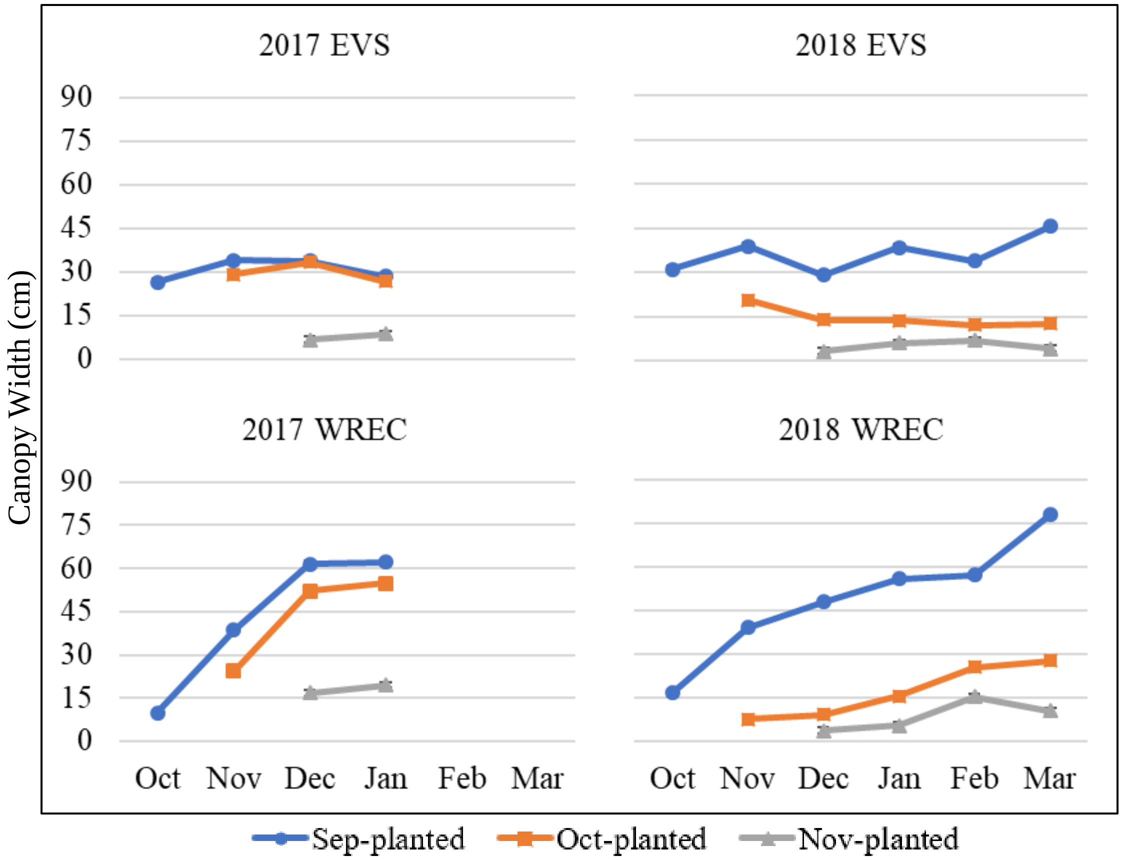

Figure 1.3. Average canopy width measured at monthly sampling intervals at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons. During 2017, radishes largely winterkilled at each location, so no canopy width data were collected after the Jan sampling date. Error bars do not exceed size of data points.

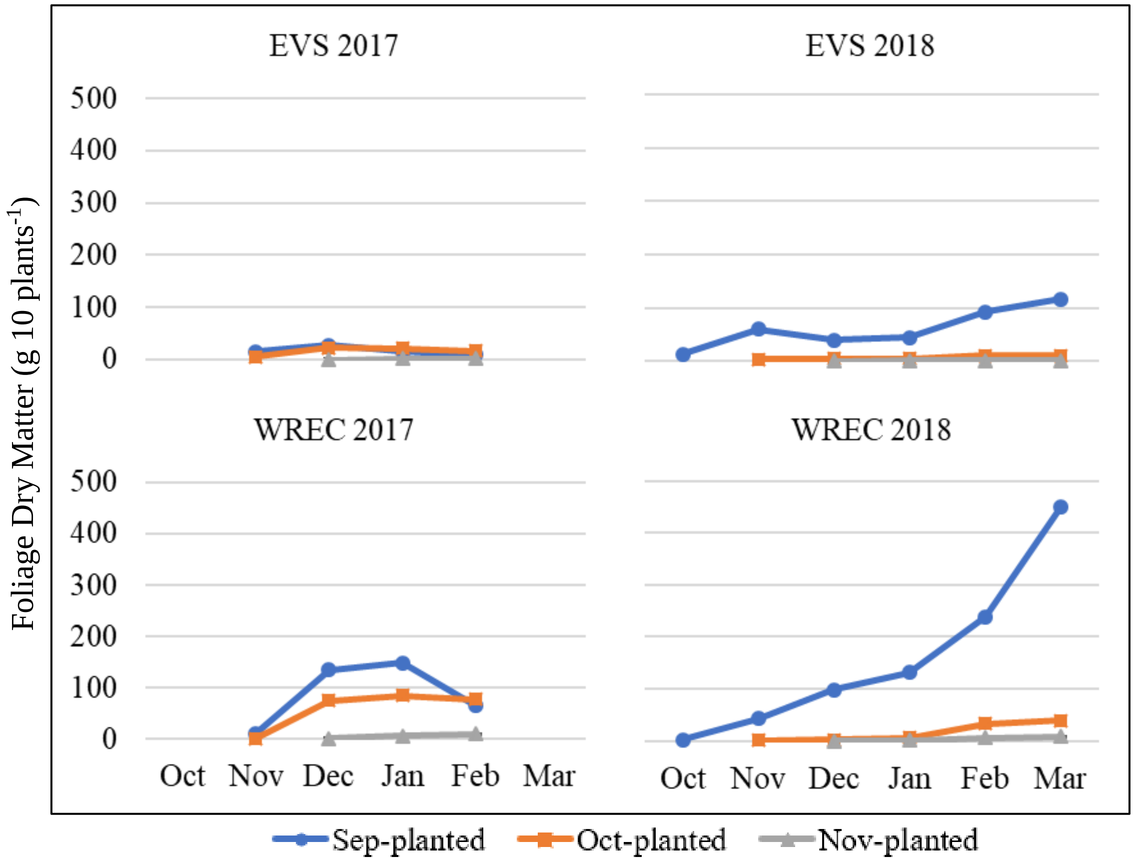

Figure 1.4. Foliage dry matter per 10 plants measured at monthly sampling intervals at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons. During 2017, radishes largely winterkilled at each location, so no foliage dry matter data were collected after the Feb sampling date. Error bars do not exceed size of data points.

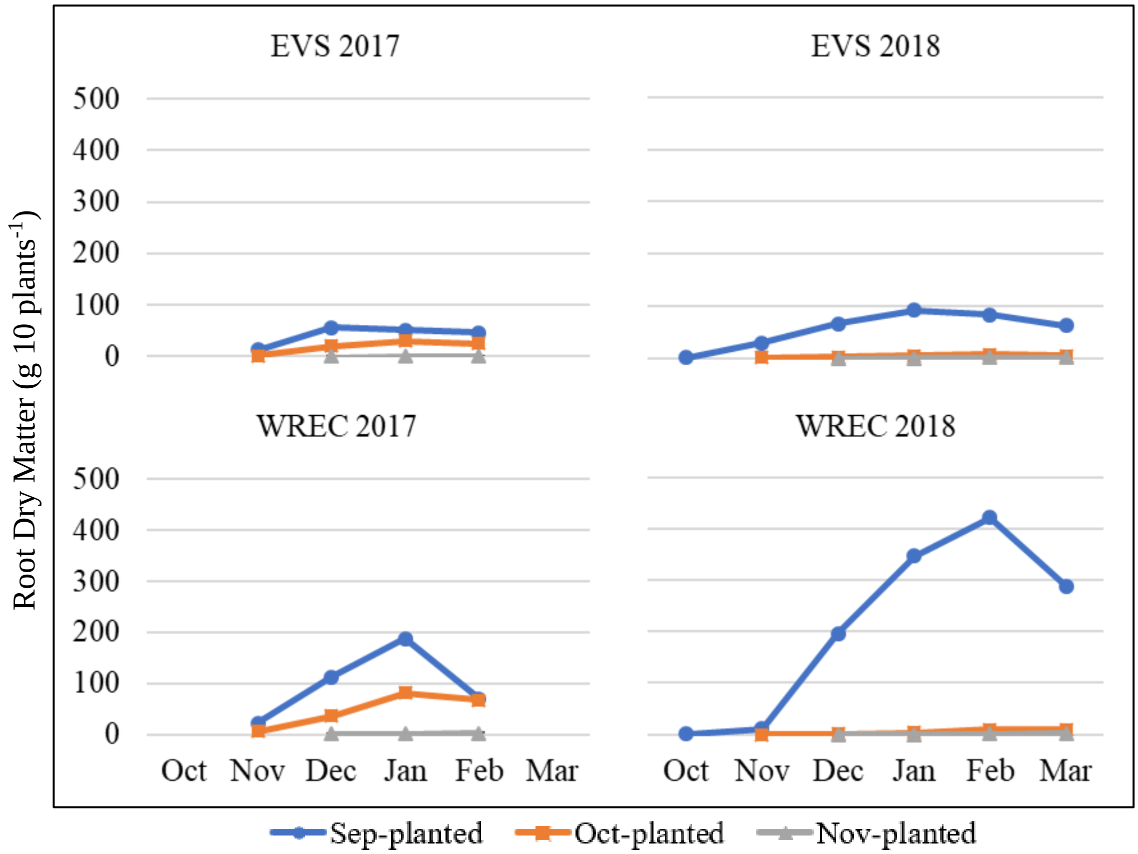

Figure 1.5. Root dry matter per 10 plants measured at monthly sampling intervals at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons. During 2017, radishes largely winterkilled at each location, so no root dry matter data were collected after the Feb sampling date. Error bars do not exceed size of data points.

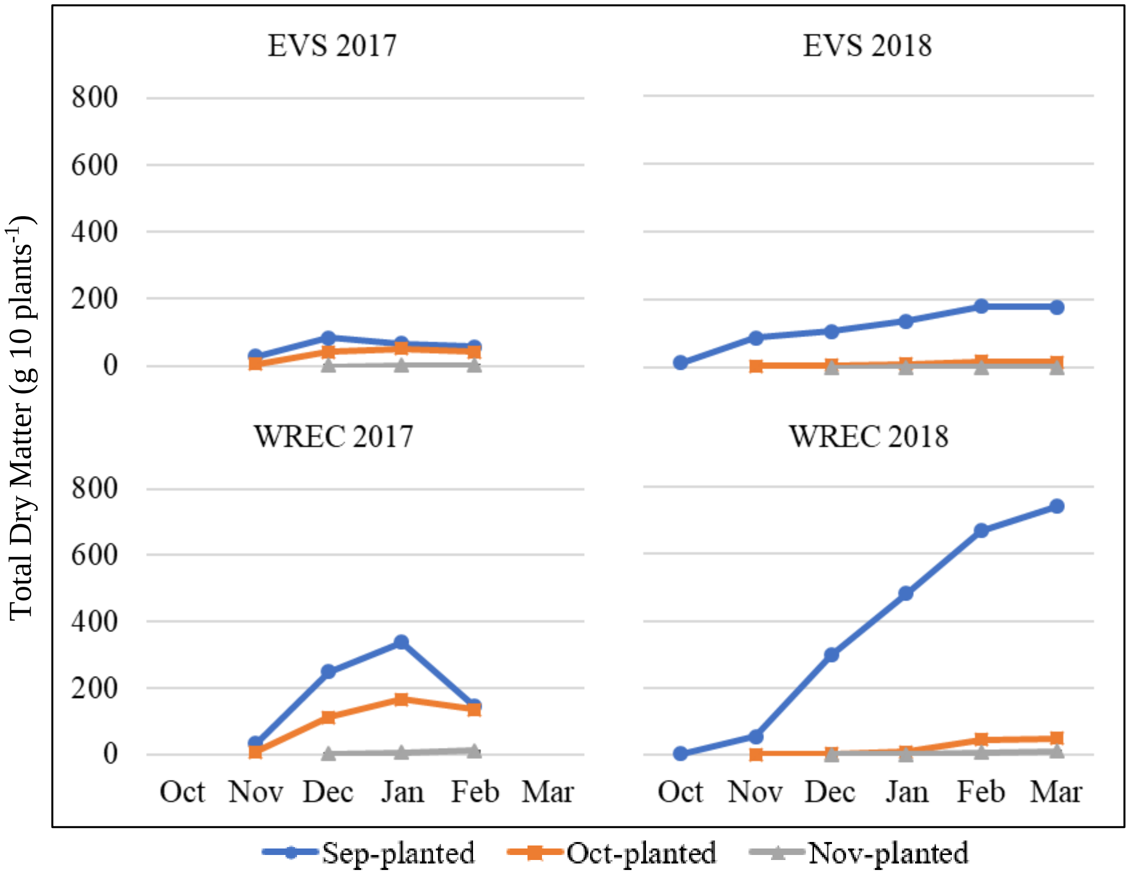

Figure 1.6. Total dry matter per 10 plants measured at monthly sampling intervals at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons. During 2017, radishes largely winterkilled at each location, so no total dry matter data were collected after the Feb sampling date. Error bars do not exceed size of data points.

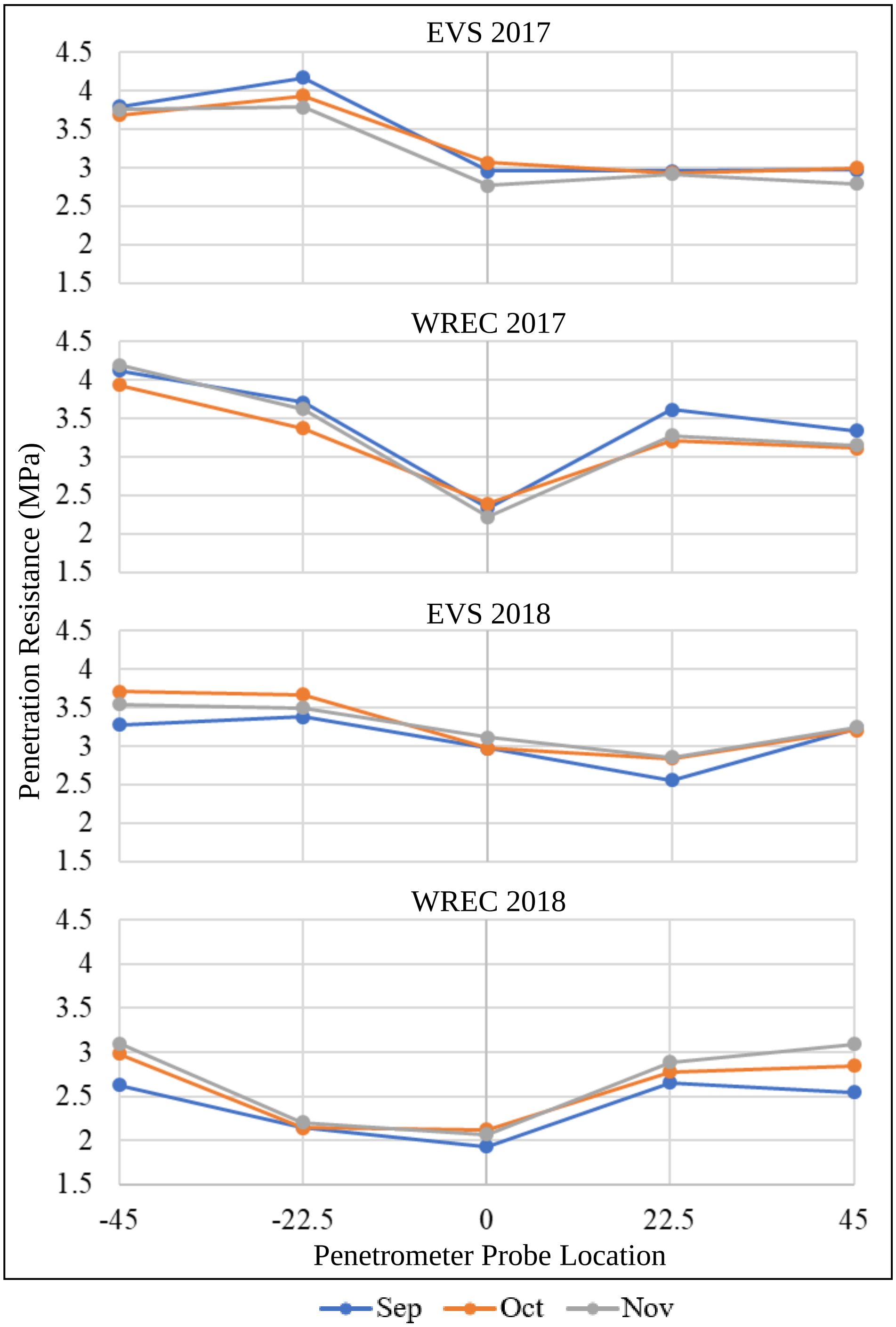

Figure 1.7. Penetration resistance for each planting date by penetrometer probe location (cm from center probe) at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as '2017') and 2018-19 (noted as '2018') growing seasons.

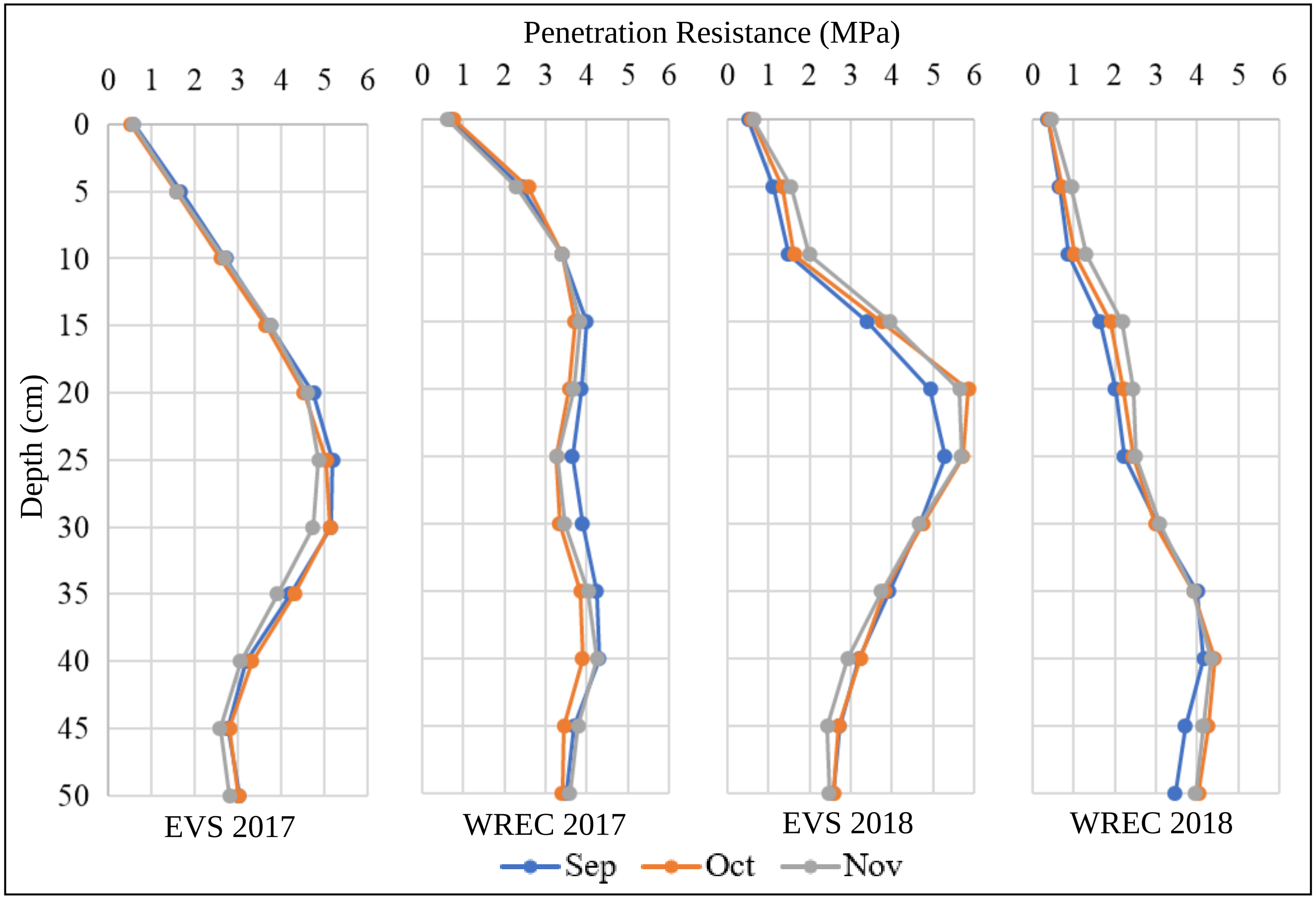

Figure 1.8. Penetration resistance by depth for each planting date at E.V. Smith Research Center (EVS) in Shorter, AL, and Wiregrass Research and Extension Center (WREC) in Headland, AL during the 2017-18 (noted as ‘2017’) and 2018-19 (noted as ‘2018’) growing seasons.

III. Penetration of Forage Radish into a Compacted Coastal Plain Soil

Abstract

Soil compaction in row cropping systems often results from intensive farming practices such as the use of heavy machinery. Compaction may reduce yields and plant vigor where mechanical means of compaction alleviation are not available or economical. Forage radish cover crops have been proposed as a potential tool to replace or complement mechanical methods of compaction alleviation, such as subsoiling, by producing a large taproot that can grow into compacted soil layers and create low-resistance pathways for subsequent crop roots. To test the ability of radish roots to alleviate compaction, a greenhouse study was conducted in Auburn, AL to determine the ability of radish taproots to penetrate compacted topsoil in 40 cm PVC cylinders. Two radish cultivars (i.e., 'Tillage' and 'Smart') were planted into the PVC cylinders with and without a constructed hardpan (>1.7 g cm^{-3}). Canopy width and above ground root length data were collected weekly. Cylinders were opened after three months of growth to observe total root length and growth behavior. While no radish penetrated the constructed hardpan, 'Tillage' radishes produced wider canopies and longer aboveground and total root lengths than 'Smart' radishes. Radishes grown in compacted cylinders produced more foliage and total dry matter than those grown in uncompacted cylinders. These results indicate that while radish cultivars may have marked growth pattern and morphological differences, there is little evidence that those differences may lead to greater penetration into compacted soil layers.

Introduction

The effect of repeated traffic over a field often leads to the formation of a root and water-limiting layer called a hardpan (Soil Science Society of America, 2008). In tilled soils, hardpans—a common feature of many southeastern U.S. soils—generally form immediately below the maximum depth of tillage, with no-tillage practices forming the shallowest pan, conventional tillage forming an intermediate pan, and subsoiling forming the deepest pan (Raper et al., 1998; Clark et al., 2003). This effect often results in an increased root density in the upper five cm of the soil profile in conservation systems and a more evenly distributed root system throughout the soil profile in conventional tillage systems (Barber, 1971; Izumi et al., 2009). Subsoiling has been used in conjunction with conservation tillage systems to break up compacted soil layers and allow roots to penetrate deeper into the soil. One region where this technique has been successful is the Tennessee Valley region of Alabama, where cotton yields decreased after the adoption of no-till practices due to compaction in the fine-textured soils of the region (Raper et al., 1998, 2000b; a). Even in the sandy Coastal Plain regions of the Southeast, strip-tillage to reduce soil compaction has led to greater cotton and corn yields and returns over variable costs than no-tillage (Box and Langdale, 1984; Schomberg et al., 2006).

First proposed by Elkins (1985) then by Cresswell and Kirkegaard (1995), the idea of using "plant roots as tillage tools" or as "bio-drilling" agents has seen renewed interest with the popularity of brassica cover crops. Using a "drilling" species such as forage radish, low-resistance root channels are formed through compacted soil, increasing the ability of subsequent crop roots to access subsoil moisture and a larger possible rooting volume. This was best illustrated in a study by Williams and Weil (2004) in which forage radish roots penetrated compacted soil layers and provided low-resistance root channels that were utilized by the succeeding soybean crop in compacted Ultisols in Maryland. This effect, which was enhanced by drought conditions, increased soybean yield in forage radish treatments, planted both as a monoculture and in a mixture with rye, compared to no cover crop treatments. Another study by Chen and Weil (2010) found that in the Mid-Atlantic Coastal Plain, forage radish decreased penetration resistance more than rapeseed (another tap-rooted Brassica species) or rye under three levels of induced compaction in a field. Furthermore, compaction levels had no significant effect on root or shoot dry matter of forage radish, with the number of radish roots increasing with increased soil strength (Chen and Weil, 2010). The ability of forage radish to decrease penetration resistance and/or increase porosity has been observed in other studies from Maryland (Chen et al., 2014), Poland (Głąb and Kulig, 2008), and Denmark (Kadžienė et al., 2011; Abdollahi and Munkholm, 2014).

Conversely, other studies have shown either no net effect of forage radish on soil properties (Acuña and Villamil, 2014) or a texture-dependent effect on soil properties (e.g., no effects in coarse-textured soils) (Chen et al., 2014). Other evidence points to Brassica cover crops relying primarily on pre-existing root pores rather than creating their own channels in high-strength soils (Cresswell and Kirkegaard, 1995). Although forage radish roots can grow below 2.24 m (Kristensen and Thorup-Kristensen, 2004), studies from Maryland have observed radish roots growing 10-15 cm deep before roots began to grow horizontally (Williams and Weil, 2004). Other studies have observed roots extending 15-30 cm into the soil, and after decomposing, leaving holes approximately 5-10 cm deep (White and Weil, 2011). In the same study, roots were occasionally observed growing horizontally before reaching a pre-existing root channel in which to grow vertically.

The effect of radish cover crops on compaction alleviation in field conditions are well-studied in the Mid-Atlantic, but research is needed in the southeast Coastal Plain to assess the ability of radishes to penetrate soil compaction layers. Thus, the objective of this study was to investigate the ability of radish cover crops to penetrate compacted soil. Furthermore, this study will assess differences between cultivars with varying phenotypic properties regarding growth and compaction alleviation in a representative Coastal Plain soil.

Materials and Methods

This experiment was conducted during the Spring of 2019 at the Plant Sciences Research Center (PSRC) greenhouses in Auburn, AL. Soil for the experiment was collected from the Wiregrass Research and Extension Center in Headland, AL. An Orangeburg (Fine-loamy, kaolinitic, thermic Typic Kandiudults) soil was selected for this experiment. Once the vegetation was removed from the site, an excavator bucket was used to collect topsoil (i.e., Ap horizon) separately from subsoil (i.e., Bt horizon). The soil was placed into large plastic containers and allowed to air dry. Once air-dried, the soil was sieved to 4 mm. Treatments consisted of two forage radish cultivars (i.e., ‘Smart’ and ‘Tillage’) and two compaction levels (i.e., uncompacted and >1.7 g cm^{-3}). The experiment was arranged in a completely randomized design and replicated five times. Radishes were planted in PVC cylinders containing an uncompacted topsoil layer, overlying a five cm compacted topsoil layer, overlying an uncompacted subsoil layer. The cylinders had an outside diameter of 40.6 cm, an inside diameter of 38.1 cm, and were 61.0 cm tall. They were constructed with a removable side panel to observe root growth at the end of the experiment.

Figures 2.1 and 2.2 illustrate the cylinder construction process. To create the compacted layer, the removeable side panel was secured with plastic wrap and zip ties. Cylinders were turned upside down and a plunger fitted with a plywood disk that matched the cylinder's inside diameter was inserted to create a flat surface in the middle of the cylinder. Next, 10.25 kg of topsoil was mixed with water to achieve approximately 12% volumetric water content and added to the top of the plywood disk in two layers. After each layer was added, the soil was tamped with an 8.75 kg weight. The cylinder was inserted into a hydraulic press and compressed using an identical plunger until the compaction zone reached five cm. In testing, this method resulted in an average bulk density of 1.78 g cm^{-3}, ranging from 1.72 to 1.83 g cm^{-3} with a standard deviation of 0.05 g cm^{-3}. Uncompacted subsoil was then added on top of the compacted topsoil layer before a base made of plywood—fitted with holes for water drainage—was affixed to the cylinder. The cylinder was turned over, and the plunger was removed before adding uncompacted topsoil on top of the compacted layer. To create cylinders without a compaction layer, the cylinder was affixed to the base and sieved subsoil was added to a predetermined level (equal to the level of subsoil in the compacted cylinders) without any additional force. Topsoil was added in a similar manner to ensure none of the soil experienced any additional compaction above what pressure the overlying soil exerted. The cylinders were placed in the greenhouse and the radishes were grown for three months (the maximum growth period that could be expected in Alabama before possibly winter-killing). Greenhouse conditions did not attempt to mimic fall temperatures, light patterns, or precipitation that radishes may experience in a field scenario. Cylinders were watered consistently, irrespective of compaction level, once every two days during the early stages of growth, then once per day once radishes were larger.

Five radish seeds were sown into each cylinder at a depth of 0.6 cm, then thinned to one radish plant per cylinder after two weeks of growth. Plant canopy width and root length above the soil was measured weekly using a ruler. After three months of growth, the side panel was removed, and soil was excavated to observe root growth with respect to the compacted layer. Root behavior was noted and categorized. Roots were removed and aboveground root length, belowground root length, total root length, and root diameter was determined. At the end of the experiment, radish roots and foliage were separated and dried for a minimum of 48 hours and weighed to determine root, foliage, and total dry matter.

Statistical Methods

All analyses were performed using the general linear model procedure (PROC GLM) in SAS version 9.4 (SAS Institute, 2013). The effects of cultivar and compaction were treated as fixed effects, while the effect of replication was treated as a random effect. All analyses utilized Tukey's HSD test for significance at $\alpha=0.05$.

Results and Discussion

Cultivar Effects on Radish Growth

In contrast to the field experiment results, there were cultivar effects in the greenhouse experiment. However, it should be noted that ‘Smart’ radishes used in the greenhouse experiment were not utilized in the field study. Cultivar affected maximum canopy width, aboveground root length, and root diameter (Table 2.1). ‘Smart’ radishes produced canopies and roots 99.3 and 7.7 cm wide, respectively—14.5 and 1 cm greater than ‘Tillage’ radishes (Figs. 2.3 and 2.4). ‘Tillage’ radishes extended 20.7 cm out of the soil and produced roots that were 40.8 cm in total length—12 and 13.1 cm longer than ‘Smart’ radish aboveground and total root length, respectively (Fig. 2.3). Further varietal differences indicated (not measured directly) that ‘Smart’ radishes produced many more lateral roots than ‘Tillage’ radishes. ‘Smart’ radish roots also grew in a “V” shape, while ‘Tillage’ radish roots maintained a more constant width along the entire root length (Fig. 2.5). There were no effects of cultivar on belowground root length or root dry matter.

Compaction Effects on Radish Growth

Compaction affected foliage and total dry matter production (Table 2.1). Radishes grown in compacted cylinders produced 75.3 and 146.8 g of foliage and total dry matter on average, respectively, which was 17.6 and 24.2 g higher than radishes grown in uncompacted cylinders (Fig. 2.6). These results are difficult to explain, as the presence of a compaction layer increased dry matter production. A possible explanation could be that since water could not percolate through the compacted layer, the topsoil layer in compacted cylinders had a higher water content than uncompacted cylinders. This increase in water content could have led to the increase in dry matter production that was observed. Additionally, the plants could have produced more foliage dry matter in an attempt to increase transpiration and decrease the water content of the surrounding soil. The average total dry matter production in this experiment was roughly twice the average total dry matter production of the highest-yielding radishes in the field experiment. This is likely explained by the warm temperatures and non-limiting water supply maintained throughout the duration of the experiment.

There were no effects of compaction on canopy width, aboveground root length, belowground root length, total root length, or root dry matter. Radishes were unable to penetrate into or through soil compaction layers, regardless of cultivar. The fact that the fleshy portion of radish taproots extended the same depth into the soil irrespective of compaction or cultivar is surprising and suggests that the ability of forage radishes to grow into deep soil layers is dependent on the small (non-fleshy) portion of the taproot. In many published studies, penetration by radish roots is measured by counting the number of roots (whether from the taproot or lateral roots) observable in a section of a soil core (Chen and Weil, 2010) or using a minirhizotron (Kristensen and Thorup-Kristensen, 2004). In this experiment, the non-fleshy portion of the taproot was observed growing laterally once the compaction layer was reached and continuing until the wall of the cylinder was encountered (Fig. 2.7). It would then follow a low-resistance path around the compaction layer (next to the cylinder wall) and into the subsoil. This observation is similar to those made by Williams and Weil (2004). In the current study, all radishes grown in cylinders with a compacted layer produced taproots that grew 19 to 20 cm deep (location of compacted layer) before growing horizontally. For cylinders which did not contain a compaction layer, all radish taproots were observed growing to the bottom of the cylinder (i.e., ~50 cm below the soil level and >61 cm from the top of the radish root) (Fig. 2.7). The result that root dry matter was unaffected by compaction or cultivar was also unexpected, especially because of the significant total root length difference between ‘Tillage’ and ‘Smart’ radishes.

Conclusion

This study illustrated varietal differences in forage radish cultivars and the effect of compaction on radish growth. After three months of growth, ‘Smart’ radishes produced both wider canopies (99.3 vs. 84.8 cm) and thicker roots (7.7 vs. 6.7 cm) than ‘Tillage’ radishes, while ‘Tillage’ radishes produced longer aboveground (20.7 vs. 8.7 cm) and total roots (40.8 vs. 27.7 cm). Other morphological differences were noted, such as increased lateral root content and “V” shape rooting pattern of ‘Smart’ radishes. There were no varietal differences with respect to belowground root length, indicating that soil conditions, rather than cultivar, may dictate how deep the fleshy taproot can grow into the soil. The presence of a compaction layer affected dry matter production, where radishes grown in compacted cylinders produced more foliage (75.3 vs. 57.7 g) and total dry matter (146.8 vs. 122.6 g). However, this could be due to the increased water content from the decreased permeability of the compaction layer. There was no effect of compaction on root dry matter for the Coastal Plain soil evaluated in this study. Since neither cultivar was able to penetrate the compaction layer and roots were observed growing around the compaction layer, it is hypothesized that radish roots will seek out paths of least resistance to grow into rather than create new channels into compacted soil layers. Further research is necessary to determine at what bulk density radish roots cease to be able to penetrate soil as well as how the location and thickness of compaction layers may affect root growth. Comparisons between cultivars in controlled settings other than those in this study would also yield valuable results for producers looking to plant a forage radish cover crop.

Table 2.1. Summary of analysis of variance (ANOVA) for canopy width, foliage dry matter (DM), root dry matter (DM), total dry matter (DM), aboveground root length, belowground root length, total root length, and root diameter in response to compaction level, cultivar, and their interaction.

	ANOVA, Pr > F							
	Canopy Width	Foliage DM	Root DM	Total DM	Aboveground Root Length	Belowground Root Length	Total Root Length	Root Diameter
Compaction Level (CL)	0.4779	0.0184	0.4494	0.0225	0.6633	0.4687	0.4564	0.8032
Cultivar (C)	0.0004	0.3633	0.8643	0.4293	0.0001	0.3611	0.0005	0.0473
CL x C	0.1861	0.9280	0.1255	0.1793	0.6121	0.2229	0.6866	0.0763

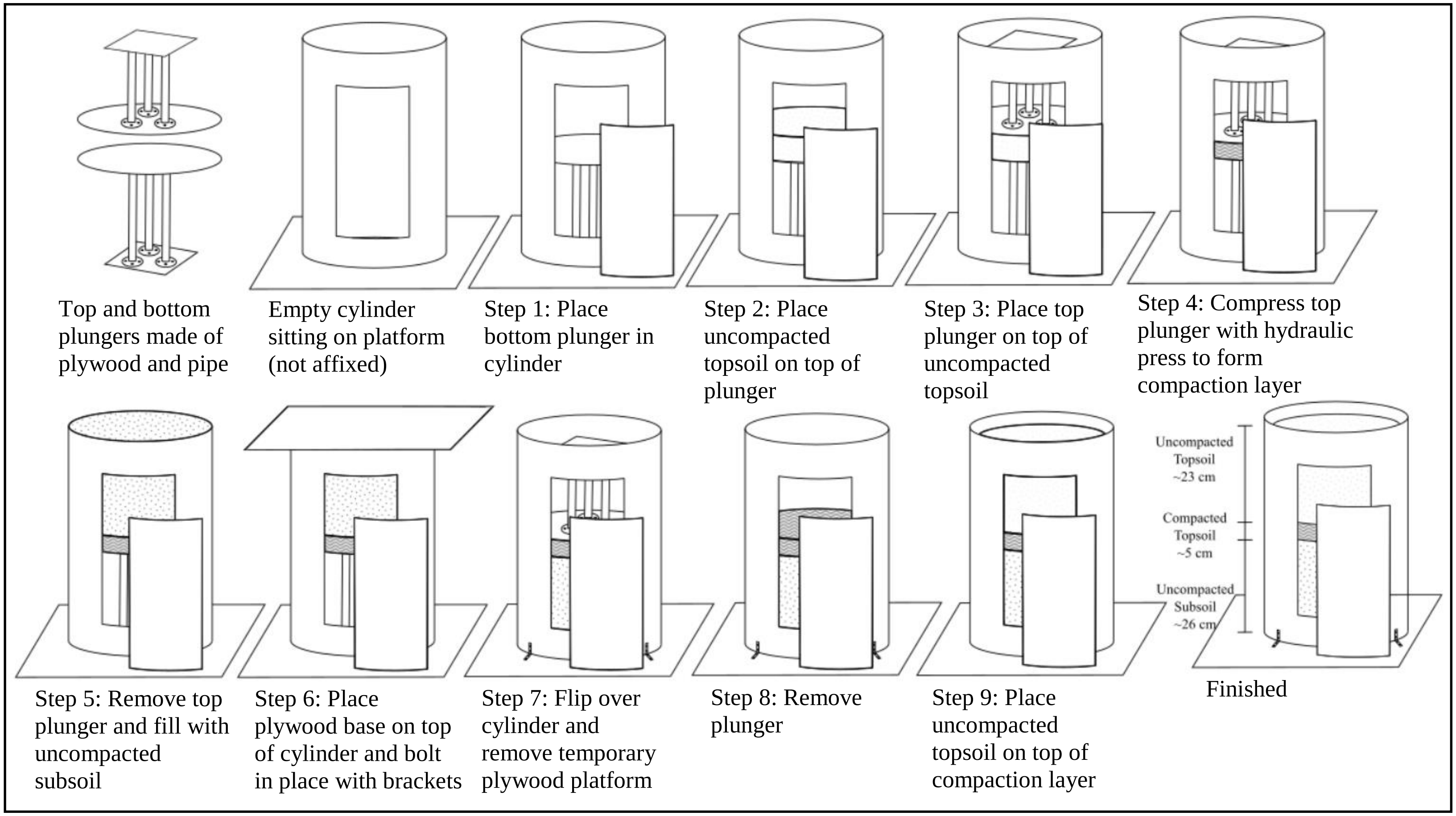

Figure 2.1. Construction process for PVC cylinder with compaction layer.

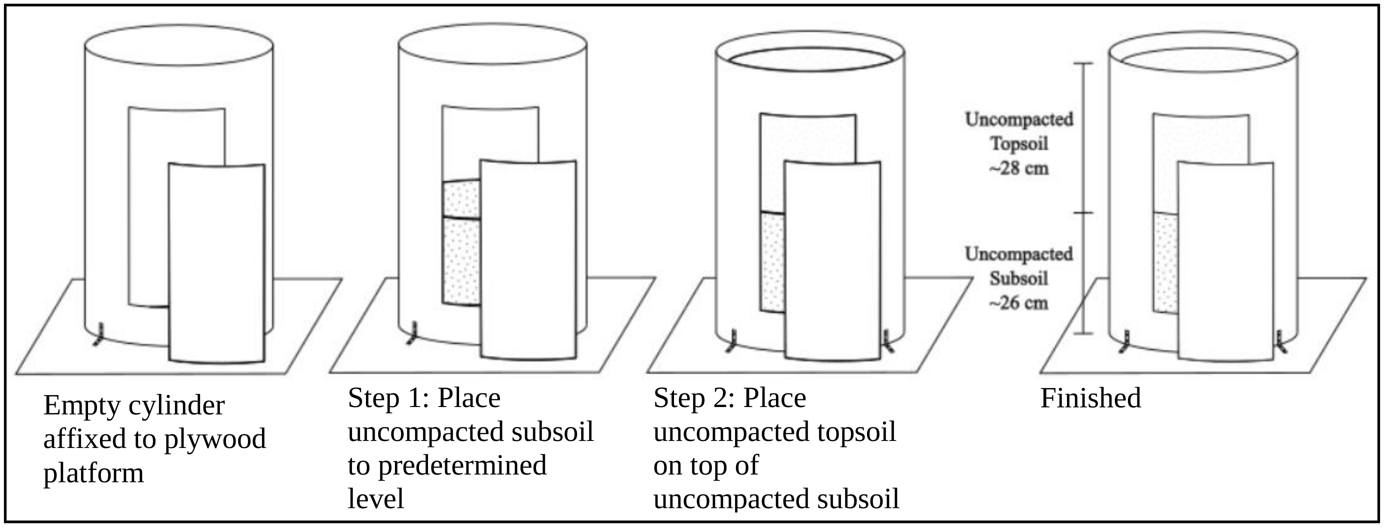

Figure 2.2. Construction process for PVC cylinder without a compaction layer.

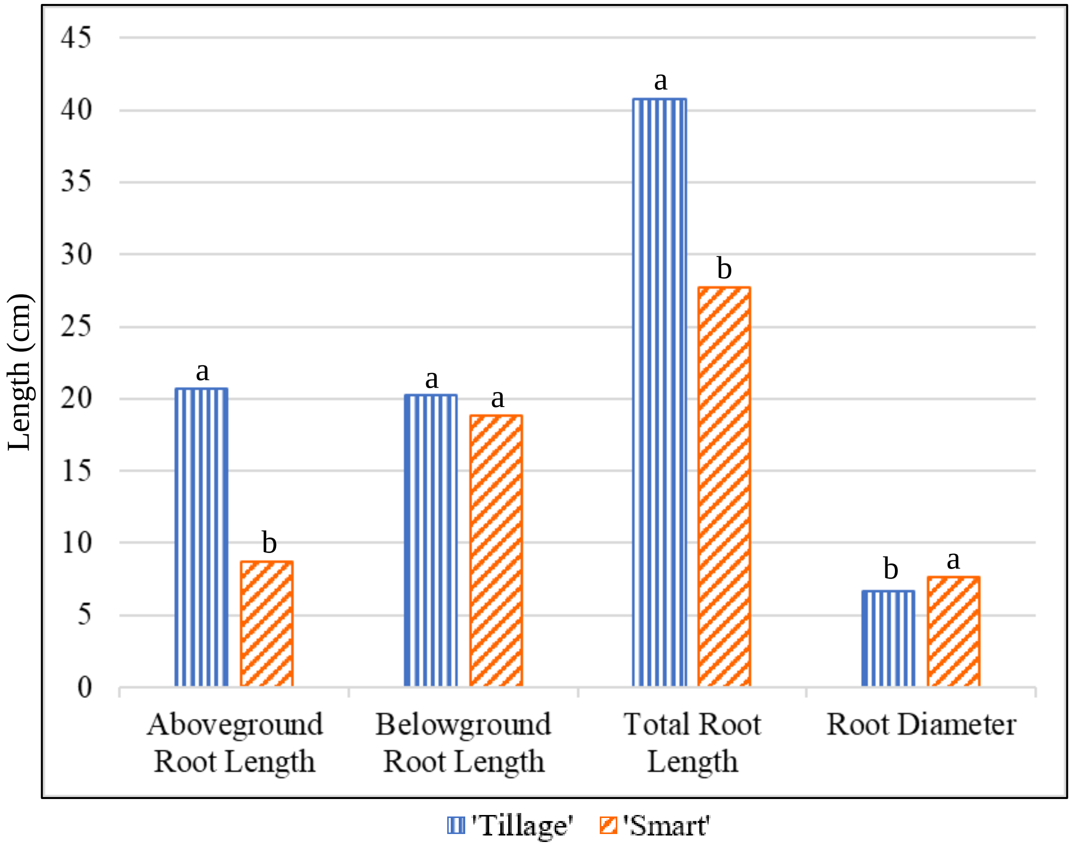

Figure 2.3. Average aboveground, belowground, and total root lengths as well as root diameter measured after three months of growth in PVC cylinders at the Plant Sciences Research Center (PSRC) in Auburn, AL. Letters denote statistical significance between cultivars for each of the root variables ($P<0.05$).

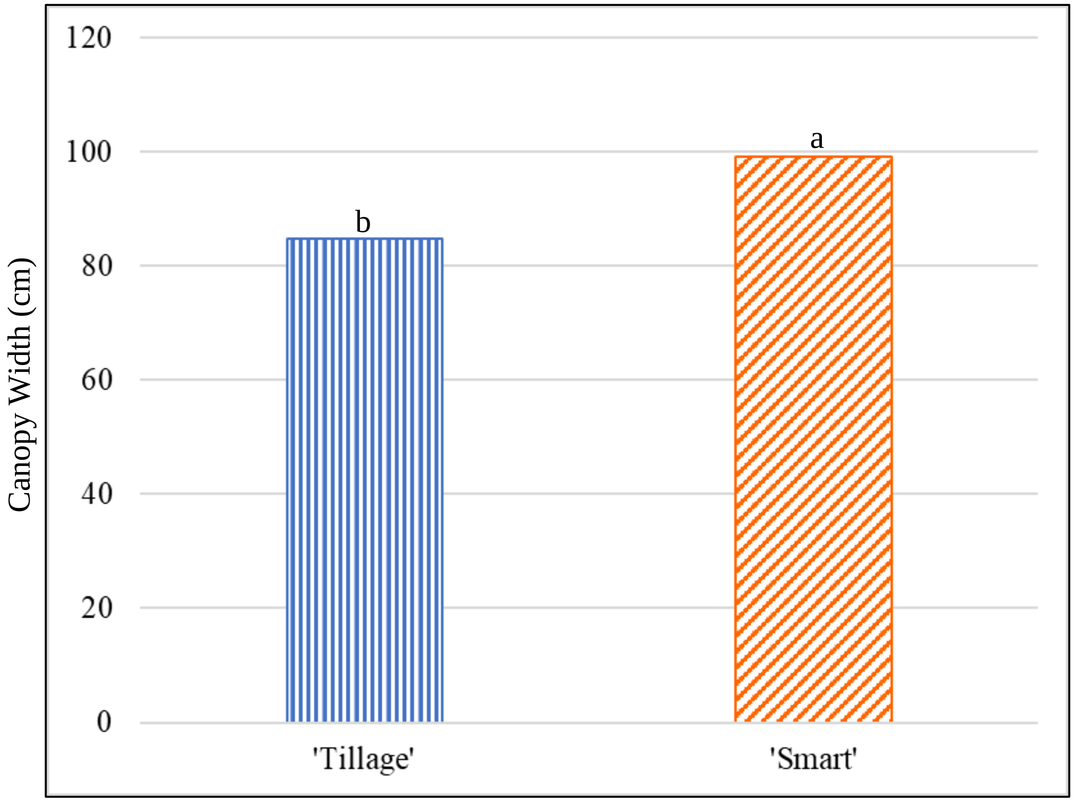

Figure 2.4. Average canopy width measured after three months of growth in PVC cylinders at the Plant Sciences Research Center (PSRC) in Auburn, AL. Letters denote statistical significance between cultivars (P<0.05).

Figure 2.5. 'Tillage' radish (left) and 'Smart' radish (right) grown in compacted cylinders to illustrate the effect of cultivar on root morphology (shape and number of lateral roots).

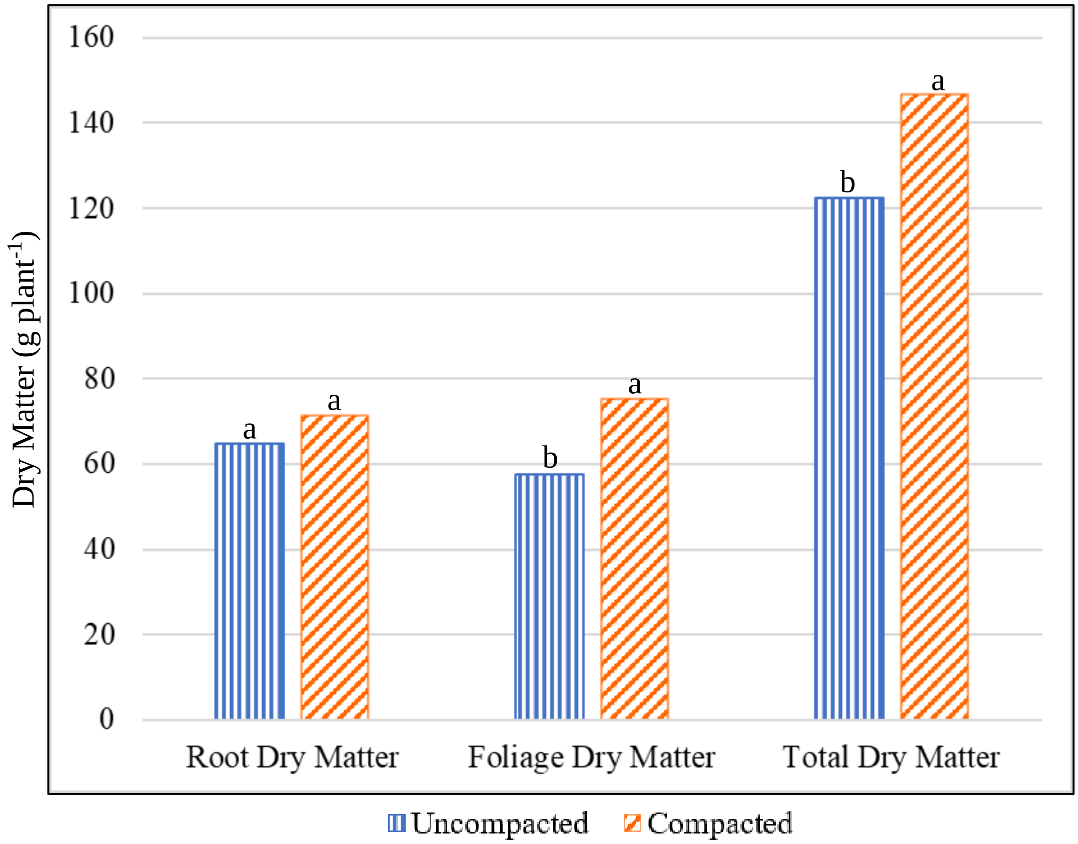

Figure 2.6. Average root, foliage, and total dry matter measured after three months of growth in PVC cylinders at the Plant Sciences Research Center (PSRC) in Auburn, AL. Letters denote statistical significance between compaction levels for each of the dry matter variables (P<0.05).

Figure 2.7. 'Tillage' radishes grown in uncompacted (left) and compacted (right) cylinders to illustrate the effect of a compaction layer on root growth.

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