BIOMASS PRODUCTION AND CHANGES IN SOIL WATER WITH COVER CROP SPECIES AND MIXTURES FOLLOWING NO-TILL WINTER WHEAT

by

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Abstract

Replacing fallow with cover crops can provide many benefits, including improved soil quality and reduced nitrogen fertilizer requirements. The addition of cover crops into no-till systems has become popular in recent years as a means of increasing cropping system intensity and diversity. A primary concern of producers in the Great Plains is the possibility that cover crops may reduce the amount of soil water stored in the profile for the next grain crop, potentially reducing yields. Multi-species cover crop mixtures that enhance the ecological stability and resilience of cover crop communities may produce greater and more consistent biomass than single species. Field experiments were established in 2013 and 2014 near Belleville and Manhattan, KS following winter wheat (*Triticum aestivum* L.) harvest to evaluate the effect of cover crop species and species complexity on changes in soil profile water content and water use efficiency. Along with a chemical fallow control, ten cover crop treatments were tested: six single species, two-three component mixes, a mix of six species, and a mix of nine species. Volumetric water content was measured using a neutron probe and a Field Scout TDR 300. Similar data were collected in 2014 from an experiment established in 2007 comparing fallow, double-cropped soybean, and four cover crop types (summer and winter legumes and non-legumes) in a no-till winter wheat-grain sorghum-soybean cropping system near Manhattan, KS. Results from both studies showed that grasses produced the most dry matter with the highest water use efficiency (up to 618 kg cm^{-1}). Fallow lost up to 7.9 cm less water than all cover crop treatments throughout cover crop growth and in the fall, but captured up to 3.4 cm less moisture in the spring than the cover crops that added residue to the soil surface. Brassica species extracted water from deeper in the soil profile than the other cover crop species. Species

complexity affected water use only relative to the proportions and productivity of their individual components, with no advantage in water use efficiency for the more complex mixtures.

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Dedication

For my brother Thelston, my role model throughout life (often of what not to do). You cannot be compensated enough for your service to our country and protection of our freedom, but here’s a thesis in your honor! And for my Mom, who left me her love for K-State and desire to help others.

Chapter 1 - Effects of Cover Crop Complexity on Soil Water and Dry Matter Production in a No-tillage Wheat-Fallow Crop Rotation

Abstract

Water is a primary concern for crop production in the Great Plains, where the most common dryland rotations include fallow following winter wheat to store water for the subsequent crop. Cover crop mixes have been marketed as a replacement for fallow to conserve water in no-tillage cropping systems. Field experiments were established in 2013 and 2014 near Belleville and Manhattan, KS to evaluate the effect of cover crop species and species complexity on changes in soil profile water content and water use efficiency. Eleven treatments: a chemical fallow control, six single species, two-three component mixes, a mix of six species, and a mix of nine species were evaluated in a randomized-complete block design with four replications. The cover crops were drilled immediately following wheat harvest and were terminated at flowering of most species. Biomass was hand harvested at termination. Volumetric soil water content was measured using a neutron probe to depths of 2.59 and 1.37 m depending on location, and at the surface with a TDR 300. Sorghum-sudangrass produced the greatest amount of dry matter with the highest water use efficiency (up to 618 kg cm^{-1}). Mixtures were found to be heavily dominated by their grass component (> 70% grass), and complexity only affected water use relative to the proportions and productivity of their individual components. Species type affected water use via varying depths of water extraction, with brassicas extracting water to greater depths than all other treatments (past 1.45 m). Fallow lost up to 7.9 cm less water than all cover crop treatments throughout cover crop growth and in the fall, but captured up to 3.4 cm less moisture in the spring than the cover crops that added residue to the soil surface.

Introduction

The addition of cover crops into no-till systems has become more and more popular in recent years as a means of increasing cropping system intensity and diversity. One of the primary concerns of producers in the Great Plains is the possibility that cover crops may reduce the amount of soil water stored in the profile for the next grain crop, potentially reducing yields. In Great Plains cropping systems, the fallow period traditionally has been used to store soil water for subsequent crops, increasing the chance for successful crop establishment and growth, and stabilizing yields (Peterson et al., 1996). The amount of soil water stored during fallow depends on many factors, including the amount of residue on the soil surface, soil type, presence of plow pans and compacted zones, crop rotation, precipitation patterns, weed growth, duration of fallow, and tillage system (Stone, 2013).

The efficiency of water capture and storage during fallow periods is characterized by the precipitation storage efficiency (PSE), or the fraction of precipitation that falls in a given time period that is stored in the soil profile (Nielsen and Vigil, 2010). The PSE during fallow often is low, ranging from ten to forty percent, even with the use of reduced tillage or no-till (Hansen et al., 2012). Stone and Schlegel (2006) found that as much as five more centimeters of water are stored during fallow in a no-till system compared to a stubble mulch system with a deep silt-loam soil in a region with 42.3 cm of long-term, mean annual precipitation. At least 60% of precipitation during fallow is therefore lost to evaporation, transpiration, leaching, or runoff in this area (Stone, 2013). About 75% of annual precipitation in the Great Plains is received from April through September (Farahani et al., 1998), though high temperatures from July to September accelerate evaporation and keep precipitation capture between 10-35% during this late fallow period (Peterson and Westfall, 2004). According to Nielsen and Vigil (2010), improving PSE in fallow beyond 35% may not be possible. No-till summer fallow efficiencies have not increased since the mid-1970s and appear to be capped near 40% because of limited residue inputs (Peterson et al., 1996; Nielsen and Vigil, 2010).

Besides storing water inefficiently, summer fallow often results in soil degradation and limits farm productivity and profitability (Lyon and Peterson, 2005). The intensification of cropping systems aims to reduce the fraction of the cropping sequence in fallow, increasing biomass productivity and the fraction of precipitation utilized by crops in the system (Aiken et al., 2013). Using precipitation nearer to the time it is received increases the precipitation use efficiency of the system and ultimately enhances soil productivity via the added residue when coupled with no-till practices and adequate weed control (Peterson et al., 1996; Peterson and Westfall, 2004).

The potential of no-till cropping systems to improve soil properties and increase soil organic carbon concentrations is limited by the reduced residue inputs of crop-fallow rotations (Blanco-Canqui et al., 2011). In recent years, cover crops have been utilized to contribute organic matter to soils lacking adequate residue. Crop residues increase precipitation infiltration by protecting the soil surface from the impact of raindrops and subsequent soil crusting, thus reducing runoff (Nielsen et al., 2005). Standing crop residues can be more effective at reducing wind erosion than flat residues, and trap more snow during the winter (Blanco-Canqui et al., 2013). Cover crops have been found to enhance nutrient cycling, with legume cover crops fixing nitrogen and potentially reducing the fertilizer inputs needed for subsequent crops. They also have been found to suppress weeds and provide a habitat for beneficial insects (Lu et al., 2000; Kasper et al., 2001). The impact of cover crops on soil physical properties can be variable depending on type of cover crop, soil, tillage, cropping system, management history, and climate. Blanco-Canqui et al. (2011) found that cover cropping improved soil aggregate stability, with the greatest effect in the upper 7.5 cm. The authors concluded that use of cover crops can reduce susceptibility of a soil to compaction, and can be an effective strategy to manage compaction near the soil surface.

Greater and more consistent biomass production can be achieved by planting multi-species cover crop mixtures that enhance the ecological stability and resilience of cover crop communities. Typically, cover crop mixture studies have compared monoculture species with biculture combinations of those species, with little focus on more complex mixtures (Kuo and Jellum, 2002; Odhiambo and Bomke, 2001; Akemo et al., 2000). Some cover crop mixture studies also failed to include monoculture control treatments necessary to evaluate the potential benefits or drawbacks of the components in the different mixtures (Creamer et al., 1997; Madden et al., 2004). Wortman et al. (2012) found mixtures to be nearly as productive as the individual components grown solely, buffering against the occasional low productivity of individual species, and performing almost as well as the best individuals. They also found that productivity did not increase with greater diversity and mixture complexity (Wortman et al., 2012).

There is wide variation in the quantity and quality of biomass produced by cover crops. According to Lu et al. (2000), biomass can vary among and within species depending on soil, moisture, temperature, and the length of the growing season. The amount and quality of biomass produced by a cover crop is believed to influence the degree of beneficial effects on subsequent cash crops. For example, legumes have been found to increase the quality of a grass-based cover crop system by increasing the nitrogen concentration of the mixture through biological nitrogen fixation, and minimizing the potential for short-term nitrogen immobilization (Rannels and Wagger, 1997). Kuo and Jellum (2002) reported that including legumes with grass cover crops increased nitrogen content and lowered the C:N ratio of the residue. Legumes can also increase the productivity of subsequent grass cash crops. Balkcom and Reeves (2005) found that sunn hemp produced 7.6 Mg ha^{-1} of biomass with 144 kg ha^{-1} of N concentration within two years, increasing corn yield by 1.2 Mg ha^{-1} relative to fallow plots.

Cover crops may have beneficial impacts on soil water as well. Although cover crops use water via evapotranspiration, residues left on the soil surface after termination may conserve soil water by reducing evaporation and runoff and increasing the opportunity for infiltration during precipitation events (Blanco-Canqui et al., 2011). Long-term cover crop use builds soil organic matter, thereby increasing the soil's water holding capacity. In the short term, cover crop residue protects the soil from the impact of raindrops and improves soil infiltration. Residue also can slow evaporation by intercepting solar radiation (Lu et al., 2000). Complex cover crop mixtures may exhibit different water extraction patterns than individual species.

The negative effects of cover crops on subsequent crop yields are larger in years with little precipitation compared to years with normal precipitation (Nielsen and Vigil, 2005). Blanco-Canqui et al. (2011) found that, in regions with precipitation greater than 500 mm yr^{-1}, including cover crops replenished the water consumed during their growth by reducing runoff losses and increasing water infiltration. However, in regions with precipitation less than 500 mm yr^{-1}, cover crops can reduce the available water for the subsequent crop even with increasing water infiltration and improving soil properties. Aiken et al. (2013) found that replacing an uncropped fallow period with an oilseed crop reduced biomass, grain yield, and expected net return of winter wheat in sequences containing corn. Species and mixture selection and termination timing must be managed carefully reduce these negative impacts on soil water status.

The date of cover crop termination can impact quantity of biomass produced, nitrogen content, and C:N ratio (Wagger, 1989). Termination method can influence the effectiveness of a cover crop at controlling weeds and extracting and conserving water (Lu et al., 2000). Cover crop termination methods include herbicide application, roller/crimpers, tillage, and mowing/chopping (Balkcom et al., 2007). Killing cover crops with an herbicide is a common method used by farmers in no-tillage systems because of the potential to cover many acres quickly. A drawback to herbicide termination is the potential to establish herbicide resistant weeds when using the same mode of action throughout the crop rotation (Culpepper et al., 2008). Cover crops also can lodge in multiple directions following chemical termination, making planting into the residue more difficult. Roller/crimpers are a slower termination method, though usually an effective alternative to herbicides and tillage. They damage the plant by creating severe lodging and crimping of the stem, keeping the above ground part of the plant attached to the root system. This causes slower death and decomposition, but controls weeds for a longer period of time. Roller/crimpers work best with tall-growing cover crops and can create a more uniform mat that is easier to plant into than standing crops (Lu et al., 2000). While not an option in no-till systems, plowing the cover crop under mixes residue and places it in close contact with soil microorganisms, speeding up decomposition and mineralization of organic matter, and the release of nutrients to the following crop. When cover crops are plowed under, they can no longer be used as mulches to suppress weed growth and can stimulate the germination and growth of new weed seeds, unlike herbicide and roller/crimper termination methods. Mowing/chopping the cover crops also speeds up decomposition while still providing a mat to prevent weed emergence and protect against erosion (Reicosky and Forcella, 1998).

Water is a primary concern for crop production in the Great Plains, and as such further research is warranted to quantify how much cover crops influence the amount of soil water available to subsequent cash crops. Interest in cover crops is growing, but producers may be hesitant to commit to practices that could hinder yields of the following crop. The objectives of this study were to evaluate the effect of cover crop species and species complexity on changes in soil profile water content and water use efficiency, and to quantify their biomass quality and productivity. With respect to these objectives, we hypothesized that the change in soil water brought on by the cover crop treatments would be correlated to the quantity of biomass produced and the species composition, not mixture complexity.

Materials and Methods

Site Description

Field studies were conducted from July 2013 through February 2015 to achieve the stated objectives. Experiments were established at the Kansas State University Department of Agronomy Ashland Bottoms Research Farm approximately 8 km south of Manhattan, KS (39°07'N 96°38'W) in an area mapped as moderately well drained Wymore silty clay loam (fine, smectitic, mesic Aquertic Argiudoll), with 0 to 1% slopes (Soil Survey Staff, 2015). The same experiment also was conducted at the Kansas State University Department of Agronomy North Central Experiment Station in Belleville, KS (39°48'N 97°40'W) on a moderately well drained Crete silt loam (fine, smectitic, mesic Pachic Udertic Argiustoll), with 0 to 1% slopes in 2013, and a Butler silt loam (fine, smectitic, mesic Vertic Argiaquoll), 0 to 1% slopes in 2014. Two locations were chosen to expose any variances in cover crop productivity based on differing environmental conditions. The 30-yr mean annual precipitation and air temperature (National

Climatic Data Center, 2010) for the study regions are 905 mm and 13°C, respectively, in Manhattan, and 777 mm and 12°C, respectively, in Belleville (Figure 1.1).

Treatment Description

Eleven different cover crop treatments were established after winter wheat harvest. The cover crop species were chosen based on beneficial characteristics and popularity among extension services, cover crop seed distributors, and farmers (Sustainable Agriculture Network, 2007; Karki, 2014). Treatments included a chemical fallow control, six monoculture cover crops (two grasses, two brassicas, and two legumes), two mixtures of three components containing one of each crop type, a mix of six components containing all monoculture treatment species, and a complex mixture of nine species (Table 1.1). The treatments contained from one to nine species to establish a range of complexity and mirror marketed products.

The seeding rates for the individual species in a mixture were determined by dividing the recommended seeding rate for that species by the number of species in the mixture, also described as the substitutive approach. Wortman et al. (2012) promoted this approach to accurately evaluate the benefits of mixtures and the contributions of individual species to the mixtures. The substitutive approach avoids variable seeding densities by making the seeding rates of the mixtures proportional to the monocultures (Jolliffe, 2000). Recommended seeding rates for individual species were obtained from a combination of USDA Natural Resource Conservation Service, Cooperative Extension, cover crop seed distributor, and farmer recommendations (Sustainable Agriculture Network, 2007). Cover crops were seeded following winter wheat harvest using a no-till drill (Model 3P605NT Great Plains Manufacturing, Inc., Salina, Kansas) to a depth of 2.54 cm, with a 0.19-m row spacing. Planting dates were 18 July 2013 and 3 July 2014 for Manhattan and 19 July 2013 and 7 July 2014 for Belleville. No fertilizer was applied prior to planting or during cover crop growth, and all legumes were inoculated with the appropriate symbiont (Trabelsi and Mhamdi, 2013). Immediately after wheat harvest and before planting cover crops, the stubble was sprayed with 1915.5 g ae ha^{-1} glyphosate and ammonium sulfate at 1120.85 g ha^{-1} to control volunteer wheat and weeds at both locations. Glyphosate herbicide was applied at the same rate to the chemical fallow plots throughout the summer as needed to control weeds and volunteer wheat.

Timing of termination centered on maximizing growth while also preventing seed production and the potential to become a future weed. Termination of cover crops occurred 25 September 2013 and 16 September 2014 at Manhattan with 1915.5 g ae ha^{-1} glyphosate and 2,4-D LV4 (1135g ae ha^{-1} 2,4-D) at anthesis of most species. Poor growth in Belleville in 2013 allowed the cover crops to be terminated by frost approximately 11 November 2013 without setting seed. At Belleville in 2014, cover crops were terminated with a mower on 25 September because plant height exceeded that of the spray equipment.

Measurement of Soil Water Content

Soil water content was measured by neutron thermalization with a 503 DR Hydroprobe Moisture Gauge (CPN International, Inc., Martinez, CA) using a count duration of 16 s. Access tubes of standard type 6061-T6 aluminum tubing (o.d. 4.128 cm, wall thickness 0.089 cm) 3.05 m in length were installed in the field plots to a depth of 2.90 m at Manhattan. Tubes were 1.83 m in length and installed to a depth of 1.68 m at Belleville. Starting at a depth of 0.152 m below the soil surface, water content was measured in 0.305 m increments to 2.59 m at Manhattan and 1.37 m at Belleville. A drop-hammer was used to drive the access tubes into holes made with a sampling tube (4.128 cm o.d., Giddings Machine Company, Inc., Windsor, CO) and tractor-mounted hydraulic probe (Model GSRTS, Giddings Machine Company, Inc.). Excess soil remaining in the tubes was removed with an auger and the tubes were covered at the top with a PVC cap. There was no seal at the base of tubes. The tubes were installed after cover crop emergence and were placed in the center of each plot in areas most representative of plot cover crop growth. Standard counts were recorded before and after tube measurements at each reading date. A mean standard count was used to calculate the count ratio (CR) from each tube-measured count (CR = measured count / mean standard count). The factory calibration equation ($\theta = 0.1733*CR - 0.006923$) of the neutron probe was used to calculate volumetric water content (θ). A field calibration for the neutron probe was in progress at the time of thesis submission. Soil water content was measured in each experimental unit bi-weekly during cover crop growth and monthly after termination. Readings at the lowest four reading depths were skipped occasionally in the 2013 growing season in Manhattan to avoid submersion of the neutron probe into the water table. The soil water data, combined with daily precipitation records (recorded at a university weather station located within 0.50 km of the Manhattan site, and a National Weather Service weather station located within 3.22 km of the Belleville site), were used to estimate cover crop evapotranspiration (ET) in each plot by the water balance method, assuming runoff and drainage to be negligible. Field conditions suggested runoff was indeed negligible, as there were no signs of soil or residue movement. All soil types are classified as having insignificant leaching losses, implying that drainage through the soil profile would be unlikely (Kissel et al., 1982).

Surface soil moisture was measured using a Field Scout TDR 300 Soil Moisture Meter (rod length 12 cm, Spectrum Technologies, Inc., Plainfield, IL). Readings were taken on the same dates as neutron probe readings, with one reading per plot. The TDR 300 was calibrated to Manhattan’s Wymore silty clay loam by wetting soil samples to known water contents. A 0.005

M calcium sulfate solution was used to wet the soil to minimize dispersion. Moistened soil was packed into PVC columns (10.2 cm i.d. and 16.5 cm height) using five lifts, each 3-cm in height. Three replicates of four moisture contents were utilized. TDR 300 period readings were taken from each column after packing, as well as gravimetric samples. A calibration equation of (θ = Period*0.000214-0.412) with an $R^2 = 0.993$ and RMSE = 0.0129 $cm^3\ cm^{-3}$ was thus generated. Benor et al. (2012) also found a strong linear relationship between TDR 300 output expressed in the meter's period reading and the volumetric water content of a soil.

Measurement of Biomass and C:N

Biomass was hand harvested from a one square meter area within each experimental unit, and mixture components were sorted and weighed on site to determine their relative contributions to total biomass. Components were not sorted at Belleville in 2013 because of poor performance. Biomass sub-samples were collected from each experimental unit for dry mass determination. These sub-samples were dried in a forced-air dryer at 65°C, and then weighed to obtain dry mass. Dry samples were analyzed for total carbon and nitrogen content in the Kansas State University Soil Testing Laboratory using the dry combustion method. Water use efficiency (WUE) during the growing season was determined for all cover crop treatments. Cover crop WUE refers to the amount of aboveground biomass produced per unit of water used during the growing period.

Statistical Analyses of Data

Experimental design was a randomized complete block design with four replications. Treatments were randomly assigned to experimental units within each replication with a different randomization for each of the four experiments. Experimental units were 6.10 m wide by 13.72

m long, except at Belleville in 2014 where they were 6.10 m by 12.19 m due to field size constraints.

Analysis of variance was conducted using the GLIMMIX procedure (SAS Institute, 2004) to determine significance of treatment factors with cover crop treatments and locations as fixed effects and replications as random effects. A significant interaction was detected between all cover crop response variables and site. Therefore, cover crop responses were analyzed by site. Treatment means of response variables were separated using pair-wise t tests at $\alpha = 0.05$.

Results and Discussion

Dry Matter Productivity

Species composition of cover crop treatments show that mixtures were heavily dominated by grasses (Figure 1.2). The one exception was the Mix of PM/WR/SH at Manhattan in 2013, where the three crop types were relatively balanced (Figure 1.2a). The grasses were able to establish more quickly with high temperatures and limited moisture, as received in Manhattan 2013 and 2014 and Belleville 2013 (Figure 1.1). Creamer et al. (1997) found that grasses such as rye (*Secale cereal* L.) and barley (*Hordeum vulgare* L.), established quickly to be competitive in mixtures. The Mix of SS/TR/MRC and Mix of 9 had greater contributions from brassicas than legumes at Manhattan 2013 and Belleville 2014 (Figure 1.2a and c), but the Mix of PM/WR/SH and Mix of 6 contained similar brassica and legume composition in Belleville 2014 (Figure 1.2c), A uniform stand of volunteer wheat was present at both sites in 2013 and was included as a separate component in Manhattan's dry matter measurements except in the Mix of 9, where wheat was included in the grass category (Figure 1.2a). Plots with medium red clover contained more than 60 percent volunteer wheat at Manhattan in 2013, likely due to clover's late emergence. Medium red clover also tended to perform poorly when in a mixture with sorghum-sudangrass, as shown by its contribution of less than 2 percent to the Mix of SS/TR/MRC at all sites (Figure 1.2). Components were not sorted at Belleville in 2013 due to poor stands and growth, and the predominance of volunteer wheat.

Cover crop treatments produced different amounts of dry matter (α=0.05) at Manhattan in 2013 and at Belleville in both years (Table 1.2). Although treatment means had a range of 6375 kg ha^{-1} at Manhattan in 2014, means could not be separated because of variable emergence within plots caused by dry conditions after planting in mid-July (Figure 1.1) and non-uniform cover crop growth. Sorghum-sudangrass was among the leading dry matter producers at all sites, and medium red clover and Winfred rape were consistently among the least productive. Both Winfred rape and medium red clover are cool season crops, which would explain their poor performance in the summer months where temperatures reached 40 degrees Celsius. As a summer annual C_4 plant, sorghum-sudangrass was able to more efficiently produce biomass in high temperatures (Uliarte et al., 2012). At Belleville 2014, the mixtures of 3 and 6 produced as much dry matter as sorghum-sudangrass, and more than the Mix of 9, both brassicas, and medium red clover. All four mixtures produced as much as pearl millet at Manhattan 2013, but still less than sorghum-sudangrass. Mixtures produced the same amount of biomass as the individual grasses and tillage radish at Belleville in 2013, where growth was unfavorable (Table 1.2). Productivity of cover crop mixtures tended to reflect the relative proportions and productivity of their individual components and never exceeded the most productive single species.

Carbon and Nitrogen Contents of Dry Matter

Quality of dry matter was quantified with total carbon and nitrogen accumulation and carbon to nitrogen ratios. Sorghum-sudangrass had the greatest carbon accumulation at all sites

(Table 1.3), with pearl millet accumulating as much carbon at three of the sites. All mixes contained as much carbon as pearl millet, sorghum-sudangrass, and tillage radish in Belleville 2013, and as much as pearl millet and sorghum-sudangrass in Manhattan 2014. Species with high carbon accumulation have been found to increase soil organic matter over time, enhancing soil health and productivity (Lu et al., 2000). The mixes of 3 had the greatest nitrogen accumulation at all sites, with sorghum-sudangrass, tillage radish, Winfred rape, sunn hemp, and the mix of 6 having similarly high N accumulation at three sites (Table 1.3). Nitrogen accumulation was less in medium red clover and the Mix of 9 at three sites. Sorghum-sudangrass was the leading carbon and nitrogen accumulator of the species and mixtures tested (Table 1.3). Increasing the complexity of mixtures was not found to enhance carbon or nitrogen accumulation.

To promote the timely decomposition of organic matter and subsequent release of nitrogen, a C:N ratio between 20:1 and 30:1 is desired (Allison, 1966; Kommendahl, 1984). One of the main reasons for combining legumes and non-legumes in mixtures is to achieve these lower C:N ratios (Creamer et al., 1997). Nitrogen accumulation by legumes, through a symbiotic relationship with *Rhizobia* bacteria, can benefit non-legumes growing in mixtures through transfer of N by the roots (Giller et al., 1991). When growing a legume with a non-legume, the legume can accumulate more nitrogen than it would alone, as non-legumes will deplete soil nitrogen and foster increased biological nitrogen fixation by legumes to compensate (Ofori and Stern, 1987). Treatments with the lowest C:N ratios were the brassicas and legumes, ranging from 12:1 to 33:1 (Table1.2). Sorghum-sudangrass was among the treatments with the highest C:N ratio at all sites, ranging from 32:1 to 60:1. Mixtures had lower C:N ratios with higher legume and brassica composition. Carbon to nitrogen ratios were highly correlated to the percent of grasses in mixtures ($R=0.86$, $P < 0.05$). The Mix of PM/WR/SH at Manhattan in 2013 had less dry matter contributed from the grass component and 25 percent of dry matter production coming from sunn hemp, causing a C:N ratio as low as single species legumes (Figure 1.2 and Table 1.2). Quality of cover crop mixtures tended to reflect the relative proportions and productivity of their individual components.

Change in Soil Water to Depth

The Manhattan site received 48 mm of rainfall between first reading and cover crop termination, and 119 mm post-termination in 2013-14 (Figure 1.1). That same year, Belleville received 145 mm prior to termination, and 24 mm from termination to final reading. In 2014-15, Manhattan received 119 mm during cover crop growth, and 140 mm post-termination. Belleville received 219 mm of rainfall prior to termination of cover crops, and 128 mm post-termination.

Cover crop treatments affected soil water content at all locations during cover crop growth. Fallow exhibited a 40 percent PSE at Manhattan 2013, and 11 percent at Belleville 2013 during cover crop growth. In 2014, larger rainfall events earlier in the season (Figure 1.1) recharged the soil profiles, resulting in greater initial moisture contents, likely allowing for more water loss to evaporation throughout the season. This resulted in fallow having a zero percent overall PSE at both sites in 2014. Even with low PSEs, neutron probe readings during cover crop growth placed fallow consistently among the treatments using the least water (Tables 1.4 and 1.5). At Manhattan 2013 and Belleville 2014, fallow lost less total water than all cover crops, regardless of species complexity. At Belleville 2013, fallow lost a similar amount to evaporation as medium red clover to evapotranspiration. There was less separation between fallow and cover crops at Manhattan 2014, where fallow lost a similar amount of water to sorghum-sudangrass, medium red clover, Winfred rape, and the Mix of 6. In general, water use was unaffected by degree of species complexity.

Depth of water extraction from the soil profile varied between cover crop treatments. After cover crop termination, fallow retained more water in the top 1 to 1.4 m than all cover crops compared to readings taken at emergence or early cover crop growth (Figures 1.3, 1.4, 1.6, 1.7, 1.9, 1.10, 1.12, and 1.13). In Manhattan 2013, Winfred rape exhibited water extraction down to 2.59 meters by cover crop termination (Figure 1.4). Soil remained dry below 1.52 m in the Winfred rape treatment at the time of corn planting (Figure 1.5), indicating rainfall was not adequate enough to replenish lost moisture below 1.52 m. Similarly, tillage radish showed extraction down to 2.29 m in Manhattan 2014 by cover crop termination (Figure 1.7), with little recharge below 1 m by January (Figure 1.8). The depths to which these brassicas can extract water is largely attributed to their ability to grow long taproots (White and Weil, 2011). Mixtures containing these brassicas did not extract water to the same depths as individual brassicas, however. Extraction patterns were similar for mixtures and individual legumes and grasses.

High biomass producing cover crops that had lower PSE during the growing season because of plant water use typically showed the greatest PSE post-termination. Greater amounts of residue on the soil surface likely decreased evaporation and increased water capture and infiltration (Dabney, 1998). With the least amount of plant residue after termination, fallow ranked among the top water losers at all sites from termination to final moisture readings (Tables 1.4 and 1.5). In general, complex mixtures did not use or conserve water differently from less complex mixtures during growth or overall. The Mix of 9 used more water than the Mix of 6 during cover crop growth at Manhattan 2014, but had similar total water use. There was greater separation of treatments between termination and final moisture readings, as fallow was one of the top water losers at all sites (Tables 1.4 and 1.5). Differences in water loss between mixtures and individual species were inconsistent across sites.

Although cover crop residue increased PSE after cover crop termination, the water required to produce that residue depleted soil moisture more than growing a low biomass crop or fallow. As a result, low biomass cover crops and fallow had greater overall PSE than high biomass crops, because they had the least total water loss. Total change in soil water from first to last readings placed tillage radish, sunn hemp, and the Mix of 9 among the top water users at all sites. Winfred rape also was a top water user in three out of the four sites (Tables 1.4 and 1.5).

Water Use Efficiency

Sorghum-sudangrass was the most efficient producer of biomass per cm of water used at all sites (Table 1.6). Winfred rape and medium red clover were the least water efficient biomass producers at all sites, and tillage radish and sunn hemp were among the least efficient treatments at three out of four sites. Mixtures had similar water use efficiencies to each other and pearl millet in Manhattan 2013, sorghum-sudangrass and pearl millet in Manhattan 2014, and sorghum-sudangrass, pearl millet, and tillage radish in Belleville 2013. Water use efficiencies differed between mixtures at Belleville 2014, with the Mix of 9 being as inefficient as medium red clover, Winfred rape, tillage radish, and sunn hemp (Table 1.6).

Surface Soil Water Content

Throughout cover crop growth, fallow plots retained the most moisture in the surface 12 cm of soil while the cover crops were using water for growth, assuming no precipitation runoff (Figures 1.15, 1.16, 1.17, and 1.18). Fallow treatments were unable to capture as much water in the spring however, as plots with cover crops had added residue to prevent evaporation and better retain moisture. At all sites, fallow stayed the wettest at the surface until the fall, but became more similar to the cover crop treatments with added precipitation after termination of the cover crop. By the time of corn planting at Manhattan 2013-14, surface moisture was greater following any of the cover crops than in fallow (Figure 1.15). That separation was not observed in Belleville 2013, likely due to the small amounts of residue produced by all cover crop treatments (Figure 1.16).

In many areas of Kansas, water availability is the deciding factor for cropping system management practices. When switching to no-till, cropping systems can be intensified because of increased stored available water (Norwood, 1999; Nielsen et al., 2005). In areas of Kansas with greater annual precipitation, year-to-year variability in precipitation amount and distribution can still cause a high degree of uncertainty in cropping system production. Previous studies in Kansas have suggested that cover crops might use too much soil water, reducing crop yields to an unacceptable level, but the negative effects of cover crops were minimized with earlier termination dates (Schlegel and Havlin, 1997). Regions with low annual precipitation may face greater challenges to system productivity and sustainability. System profitability and sustainability will be decided by the unique needs of the individual producer. Yield reductions may be acceptable to some if soil quality is improved long-term. The large selection of cover crops available to producers allows them to choose the species and mixtures of species that best fit their crop rotation and individual needs at relatively low costs.

Conclusions

During the cover crop growing season, high biomass producing cover crops had greater water use than fallow or cover crops producing less biomass. After cover crop termination, water capture was greatest in treatments that had produced greater amounts of dry matter. Brassicas exhibited water use beyond two meters of soil depth. On average, grass species produced greater biomass than the brassicas and legumes they were compared to in this study. Grasses tended to dominate the composition of mixtures when seeded proportionally to their individual rates, and also raised the C:N ratios of mixtures. Sorghum-sudangrass produced the most aboveground biomass and was the most water use efficient of the species and mixtures tested. Mixtures showed similar water use and biomass production to each other, regardless of complexity. They performed similarly to the single species that were most prevalent in their mixture composition. Change in soil water content brought on by the cover crop treatments was found to be related to species composition and quantity of biomass produced, not mixture complexity.

References

Aiken, R.M., D.M. O'Brien, B.L. Olsen, and L. Murray. 2013. Replacing fallow with continuous cropping reduces crop water productivity of semiarid wheat. Agron. J. 105:199-207.

Akemo, M.C., E.E. Regnier, and M.A. Bennett. 2000. Weed suppression in spring-grown rye (*Secale cereale*)-pea (*Pisum sativum*) cover crop mixes. Weed Technol. 14:545-549.

Allison, F.E. 1966. The fate of nitrogen applied to soils. Adv. Agron. 18:219-258.

Balkcom, K.S., and D.W. Reeves. 2005. Sunn-hemp utilized as a legume cover crop for corn production. Agron. J. 97:26-31.

Balkcom, K., H. Schomberg, W. Reeves, A. Clark. 2007. Managing cover crops in conservation tillage systems. In: Andy Clark, Managing cover crops profitably. Sustainable Agriculture Network, Beltsville, MD. 44-61.

Benor, M., G.J. Levy, Y. Mishael, and A. Nadler. 2012. Salinity effects on the Fieldscout TDR 300 soil moisture meter readings. Soil Sci. Soc. Am. J. 77:412-416.

Blanco-Canqui, H., J.D. Holman, A.J. Schlegel, J. Tatarko, and T.M. Shaver. 2013. Replacing fallow with cover crops in a semiarid soil: effects on soil properties. Soil Sci. Soc. Am. J. 77:1026-1034.

Blanco-Canqui, H., M.M. Mikha, D.R. Presley, and M.M. Claasen. 2011. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Sci. Soc. Am. J. 75:1471-1482.

Creamer, N.J., M.A. Bennett, and B.R. Stinner. 1997. Evaluation of cover crop mixtures for use in vegetable production systems. HortScience 32(5):866-870.

Culpepper, A.S., J.R. Whitaker, A.W. MacRae, and A.C. York. 2008. Distribution of glyphosate-resistant palmer amaranth in Georgia and North Carolina during 2005 and 2006. J. Cotton Sci. 12:306-310.

Dabney, S.M. 1998. Cover crop impacts on watershed hydrology. J. Soil Water Conserv. 53:207-213.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: the significance of cropping intensification. Soil Sci. Soc. Am. J. 62:984-991.

Giller, K.E., J. Ormesher, and F.M. Awah. 1991. Nitrogen transfer from *Phaseolus* bean to intercropped maize measured using ^{15}N-enrichement and ^{15}N-isotope dilution methods. Soil Biol. Biochem. 22:339-346.

Hansen, N.C., B.L. Allen, R.L. Baumhardt, and D.J. Lyon. 2012. Research achievements and adoption of no-till, dryland cropping in the semi-arid U.S. Great Plains. Field Crops Res. 132:196-203.

Jolliffe, P.A. 2000. The replacement series. J. Ecol. 88:371-385.

Karki, D. 2014. Cover crops after small grains. iGrow. SDSU Extension. http://igrow.org/agronomy/other-crops/cover-crops-after-small-grains (accessed 28 Feb. 2015).

Kasper, T.C., J.K. Radke, and J.M. Laflen. 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56.2:160-164.

Kissel, D.E., O.W. Bidwell, and J.F. Kientz. 1982. Leaching classes of Kansas soils. Kansas Agricultural Experiment Station, Kansas State University. Bulletin 641.

Kommendahl, T. 1984. Interaction of nitrogen use and plant disease control, p. 561-474. In: R.D. Hauck (ed.). Nitrogen in crop production. ASA, CSA, SSSA, Madison, Wis.

Kuo, S., and E.J. Jellum. 2002. Influence of winter cover crop and residue management on soil nitrogen availability and corn. Agron. J. 94:501-508.

Lyon, D.J., and G.A. Peterson. 2005. Continuous dryland cropping in the Great Plains: What are the limits? Agron. J. 97:347-348.

Lu, Y.C., A.A. Abdul-Baki, J.R. Teasdale, and K.B. Watkins. 2000. Cover crops in sustainable food production. Food Reviews International. 16:121-157.

Madden, N.M., J.P. Mitchell, W.T. Lanini, M.D. Cahn, E.V. Herrero, S. Park, S.R. Temple, and M. Van Horn. 2004. Evaluation of conservation tillage and cover crop systems for organic processing tomato production. HortTechnol. 14(2):243-250.

National Climatic Data Center. 2010. 1981-2010 Normals. National Climatic Data Center, Asheville, NC.

Nielsen, D.C., and M.F. Vigil. 2005. Legume green fallow effect on soil water content and yield of winter wheat. Agron. J. 97:684-689.

Nielsen, D.C., and M.F. Vigil. 2010. Precipitation storage efficiency during fallow in wheat-fallow systems. Agron. J. 102:537-543.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97:364-372.

Norwood, C.A. 1999. Water use and yield of dryland row crops as affected by tillage. Agron. J. 91:108-115.

Odhiambo, J.J.O., and A.A. Bomke. 2001. Grass and legume cover crop effects on dry matter and nitrogen accumulation. Agron. J. 93:299-307.

Ofori, C.F. and W.R. Stern. 1987. Cereal-legume intercropping systems. Adv. Agron. 26:177-204.

Peterson, G.A., and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144:127-138.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180-186.

Ranells, N.N., and M.G. Wagger. 1997. Nitrogen-15 recovery and release by rye and crimson clover crops. Soil Sci. Soc. Am. J. 61:943-948.

Reicosky, D.C., and F. Forcella. 1998. Cover crop and soil quality interactions in agroecosystems. J. Soil Water Conserv. 53(3):224.

SAS Institute. 2004. Release 9.1.3 ed. SAS Inst., Cary, NC.

Schlegel, A.J., and J.L. Havlin. 1997. Green fallow for the central Great Plains. Agron. J. 89: 762-767.

Soil Survey Staff. 2015. Web soil survey: Soil data mart. USDA-NRCS. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (accessed 4 Mar. 2015).

Stone, L.R. 2013. Fallow efficiency: measuring the value of fallow. KSU agronomy e-Update 387. 1 Feb. 2013.

Stone, L.R., and A.J. Schlegel. 2006. Yield-water supply relationships of grain sorghum and winter wheat. Agron. J. 98:1359-1366.

Sustainable Agriculture Network. 2007. Benefits of cover crops. In: Andy Clark, Managing cover crops profitably. Sustainable Agriculture Network, Beltsville, MD. 9-11.

Trabelsi, D., and R. Mhamdi. 2013. Microbial inoculants and their impact on soil microbial communities: a review. BioMed Research International. http://dx.doi.org/10.1155/2013/863240.

Uliarte, E.M., H.R. Schultz, C. Frings, M. Pfister, C.A. Parera, and R.F. del Monte. 2013. Seasonal dynamics of CO_2 balance and water consumption of C_3 and C_4-type cover crops compared to bare soil in a suitability study for their use in vineyards in Germany and Argentina. Agricultural and Forest Meteorology 181:1-16.

Wagger, M.G. 1989. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. Agron. J. 81:533-538.

White, C.M., and R.R. Weil. 2011. Forage radish cover crops increase soil test phosphorus surrounding radish taproot holes. Soil Sci. Soc. Am. 75:121-130.

Wortman, S.E., C.A. Francis, and J.L. Lindquist. 2012. Cover crop mixtures for the western corn belt: opportunities for increased productivity and stability. Agron. J. 104.3: 699-705.

Figures and Tables

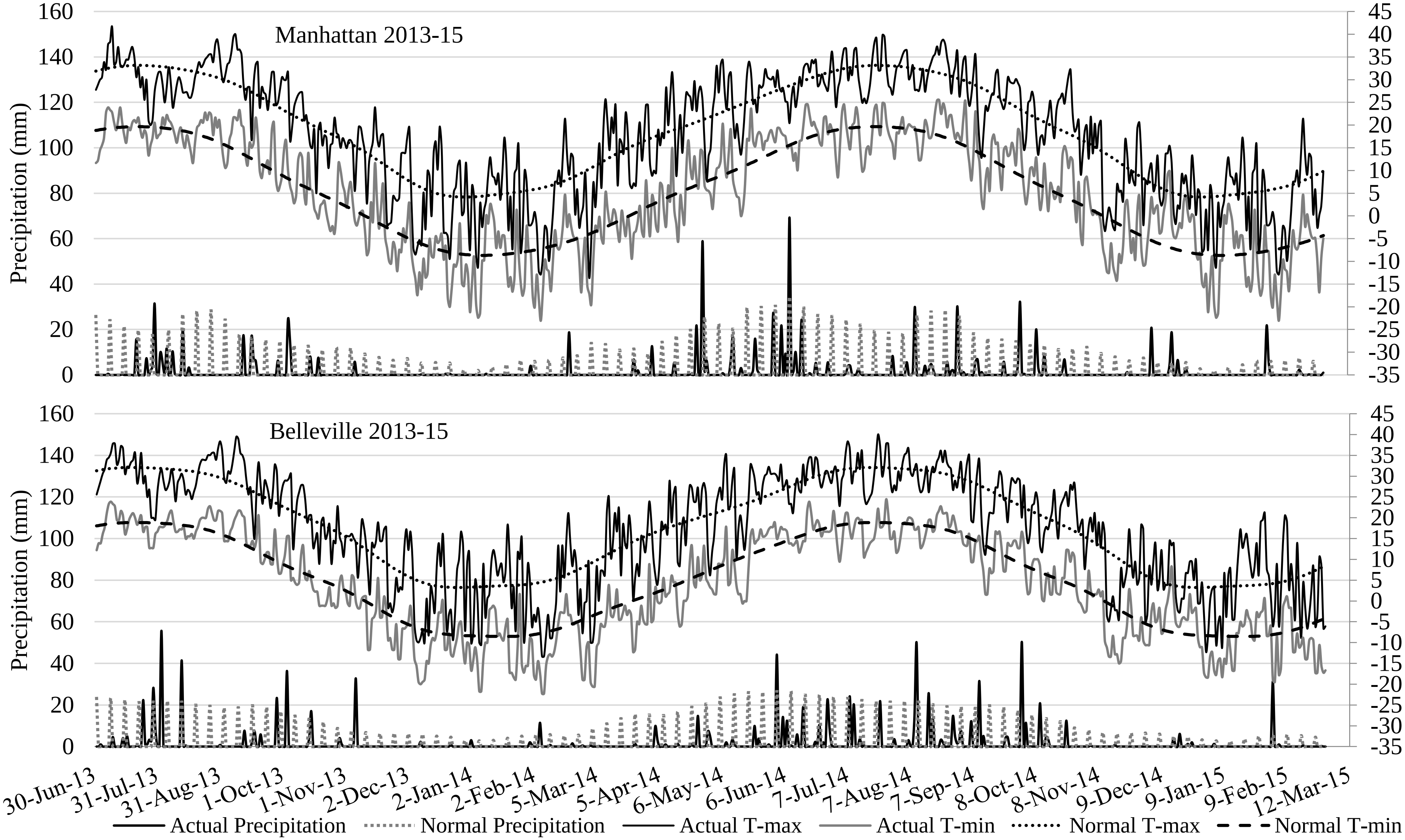

Figure 1.1 Weekly normal and actual temperature and precipitation for Manhattan and Belleville, KS.

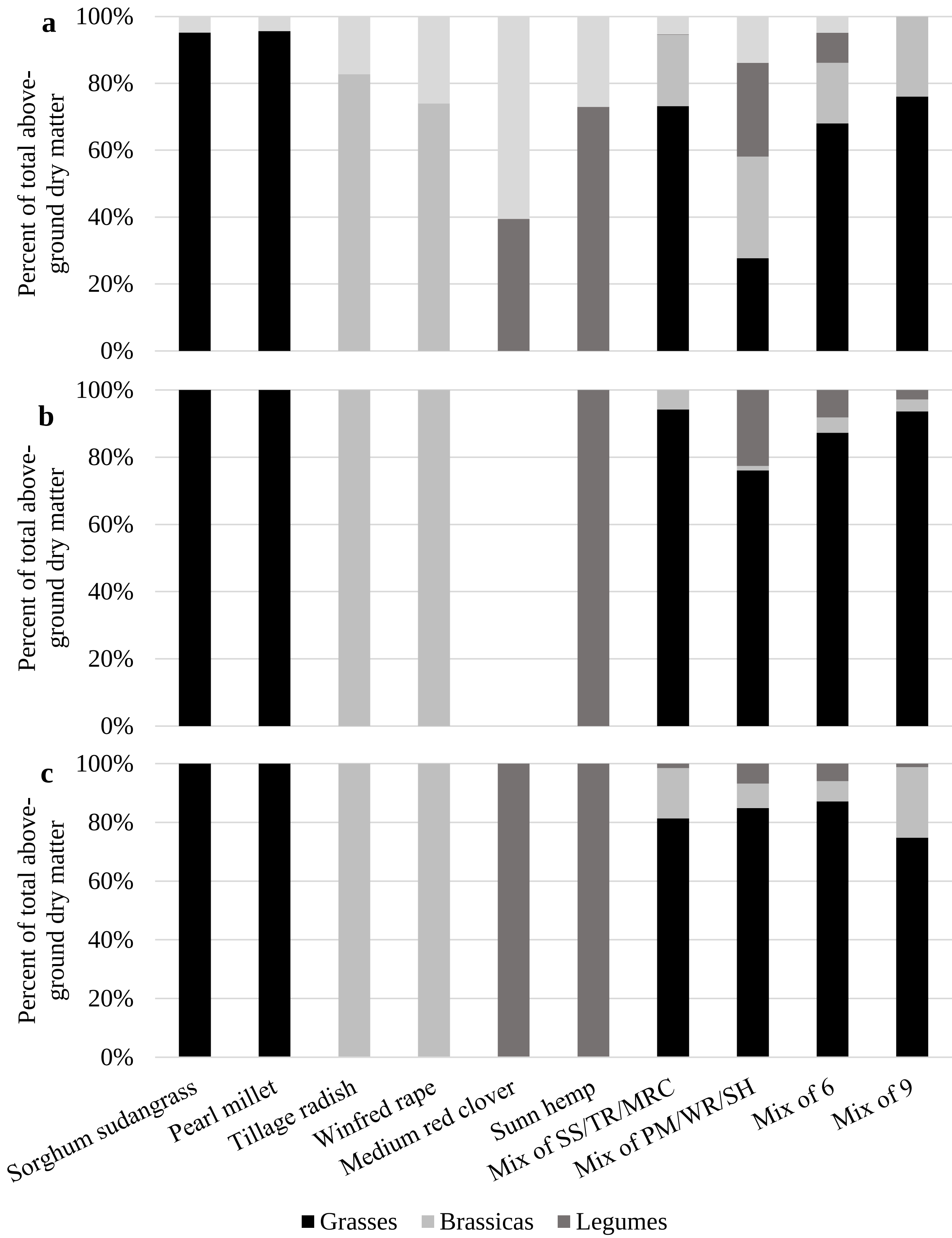

Figure 1.2 Above-ground biomass species composition for cover crops and mixtures of increasing complexity evaluated at Manhattan in 2013 (a) and 2014 (b) and Belleville in 2014 (c).

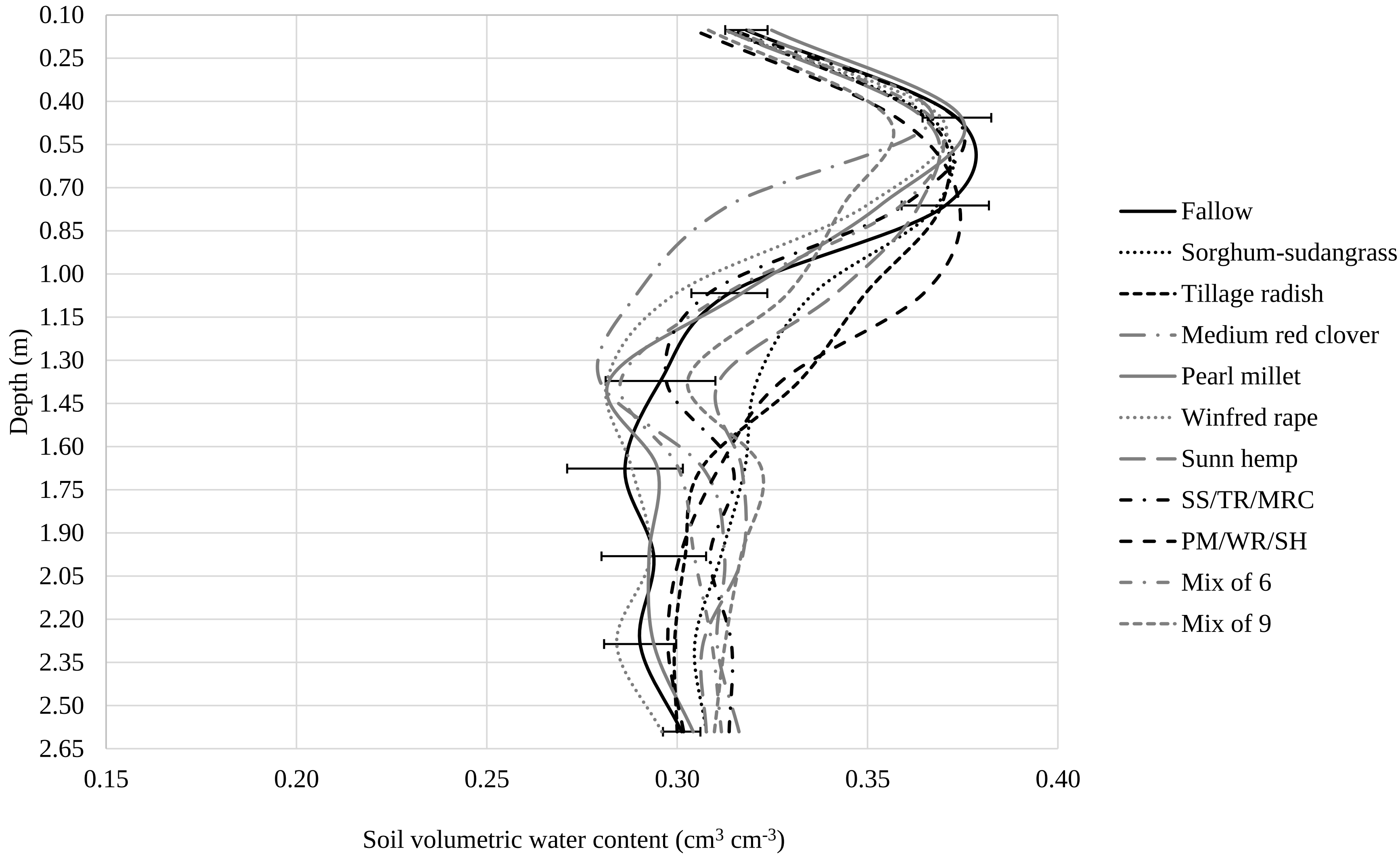

Figure 1.3 Soil volumetric water content to a depth of 2.59 meters at Manhattan, 17 August 2013, early cover crop growth.

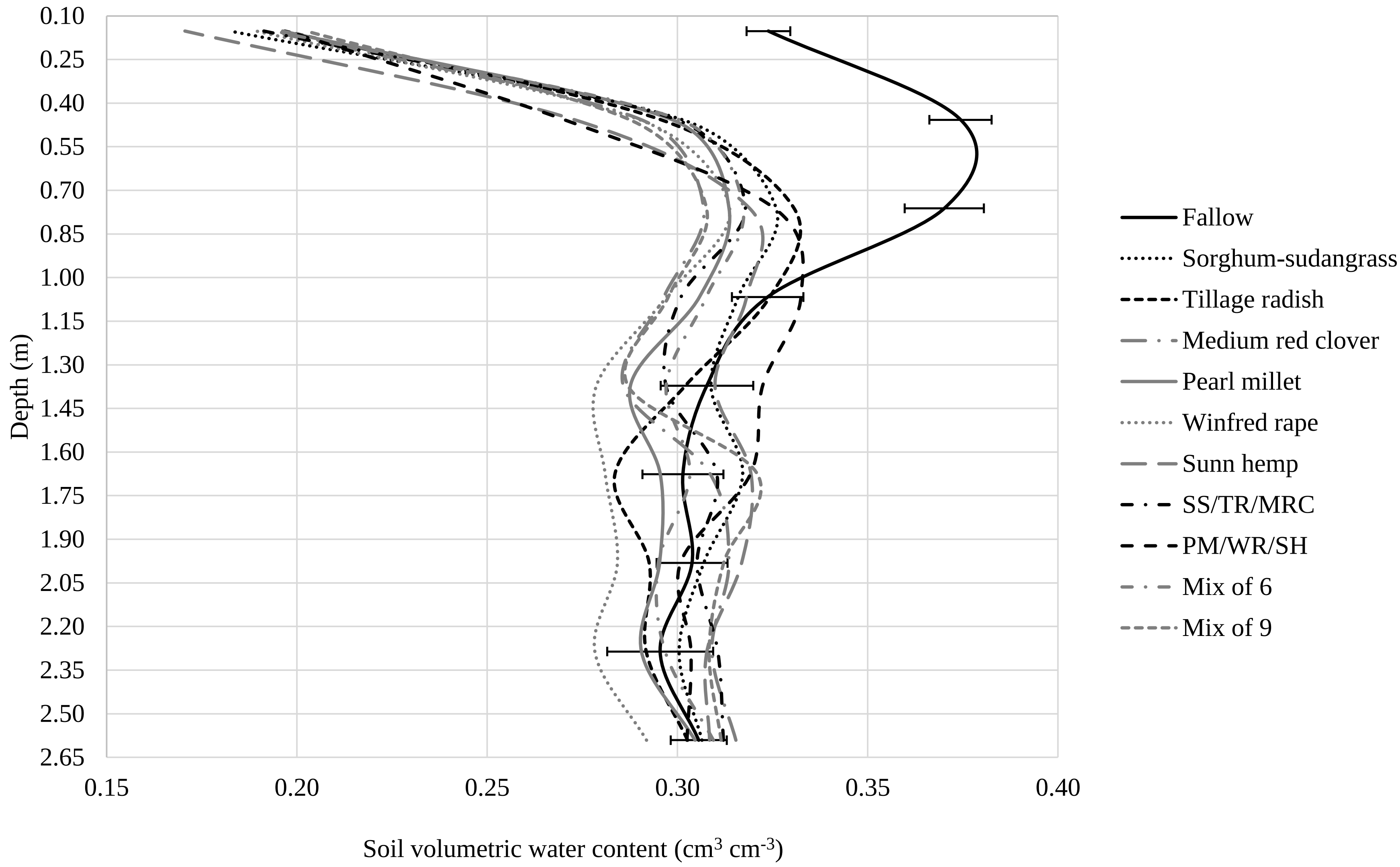

Figure 1.4 Soil volumetric water content to a depth of 2.59 meters at Manhattan, 22 September 2013, cover crop termination.

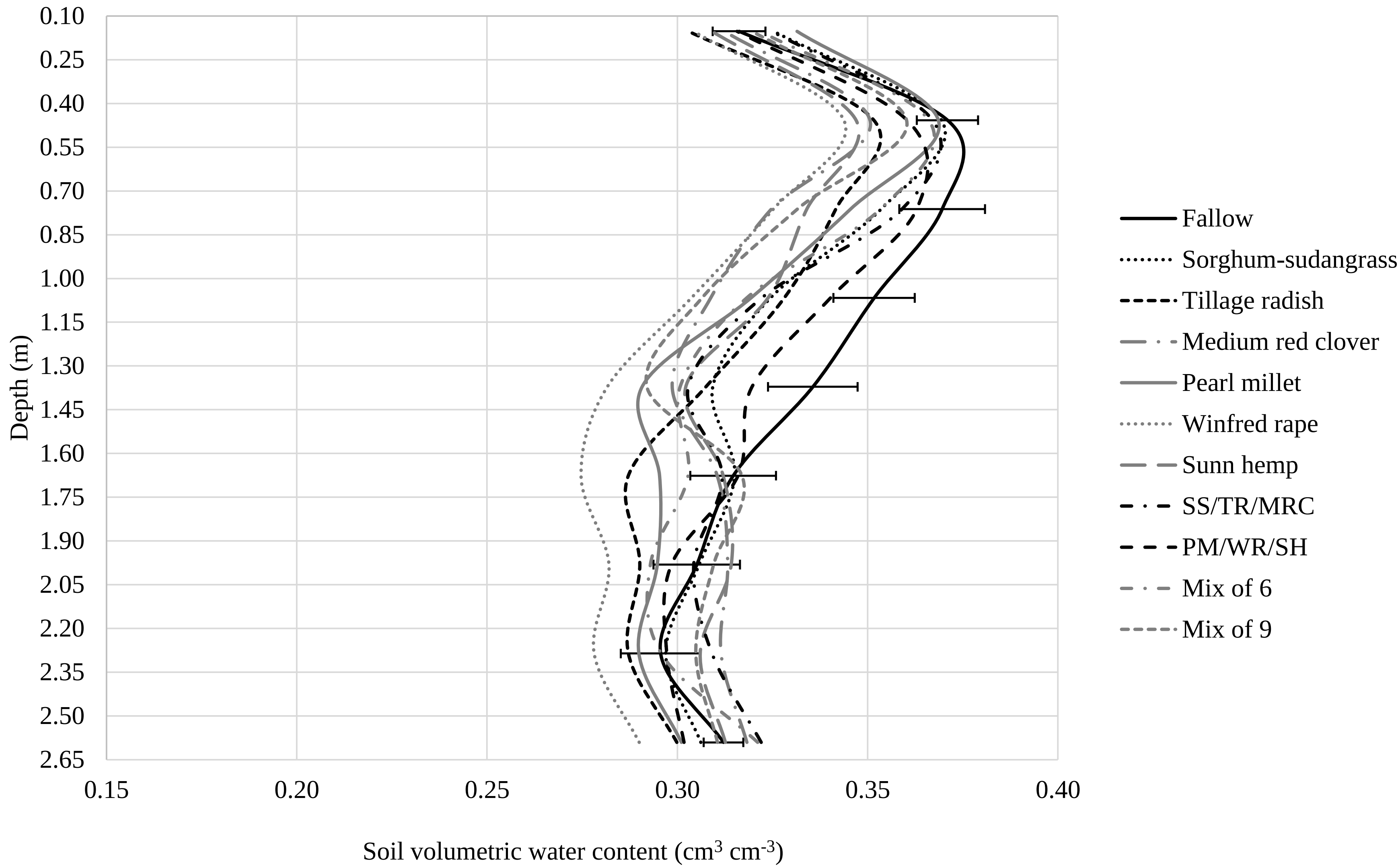

Figure 1.5 Soil volumetric water content to a depth of 2.59 meters at Manhattan, 15 April 2014, corn planting.

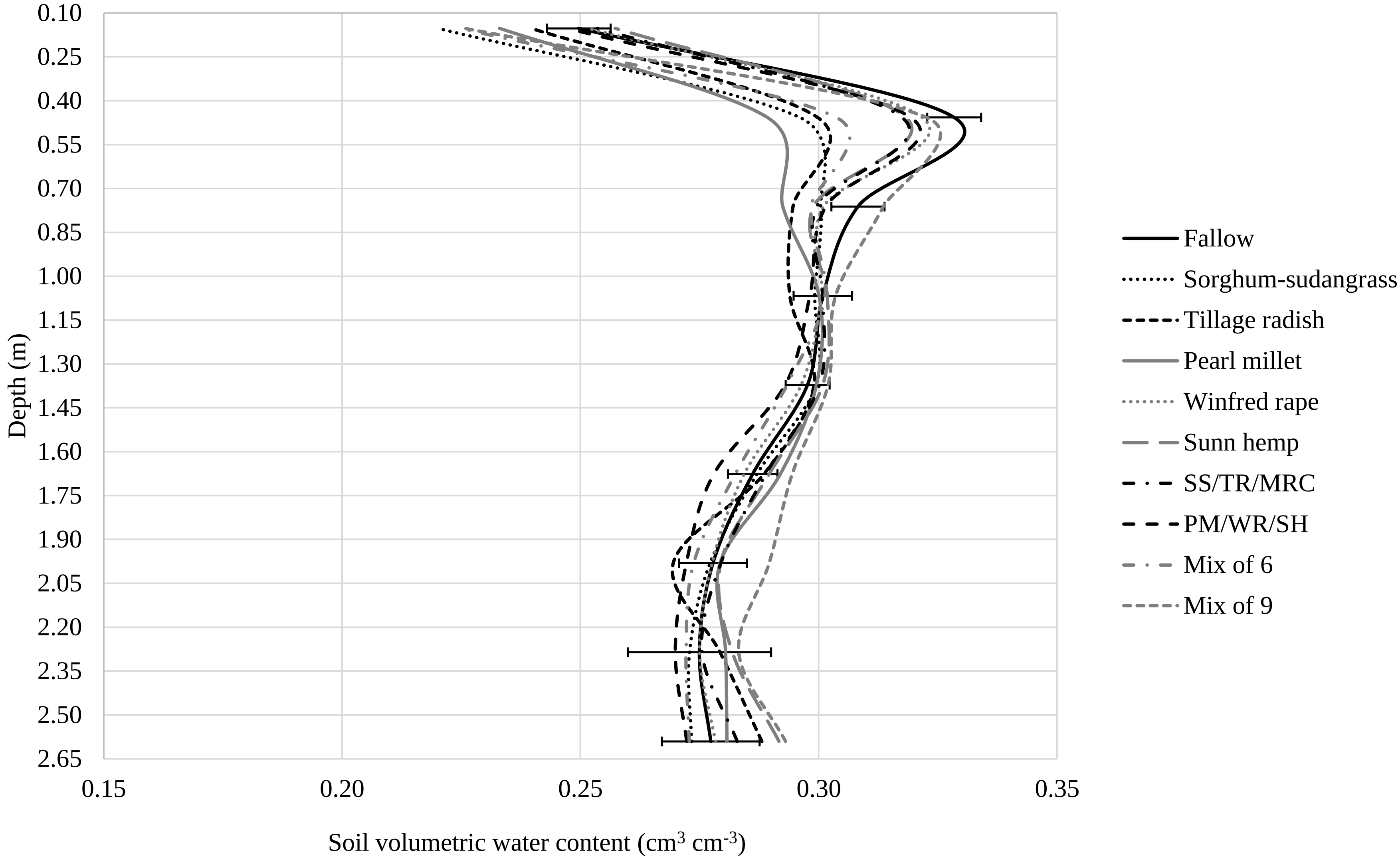

Figure 1.6 Soil volumetric water content to a depth of 2.59 meters at Manhattan, 28 July 2014, cover crop emergence.

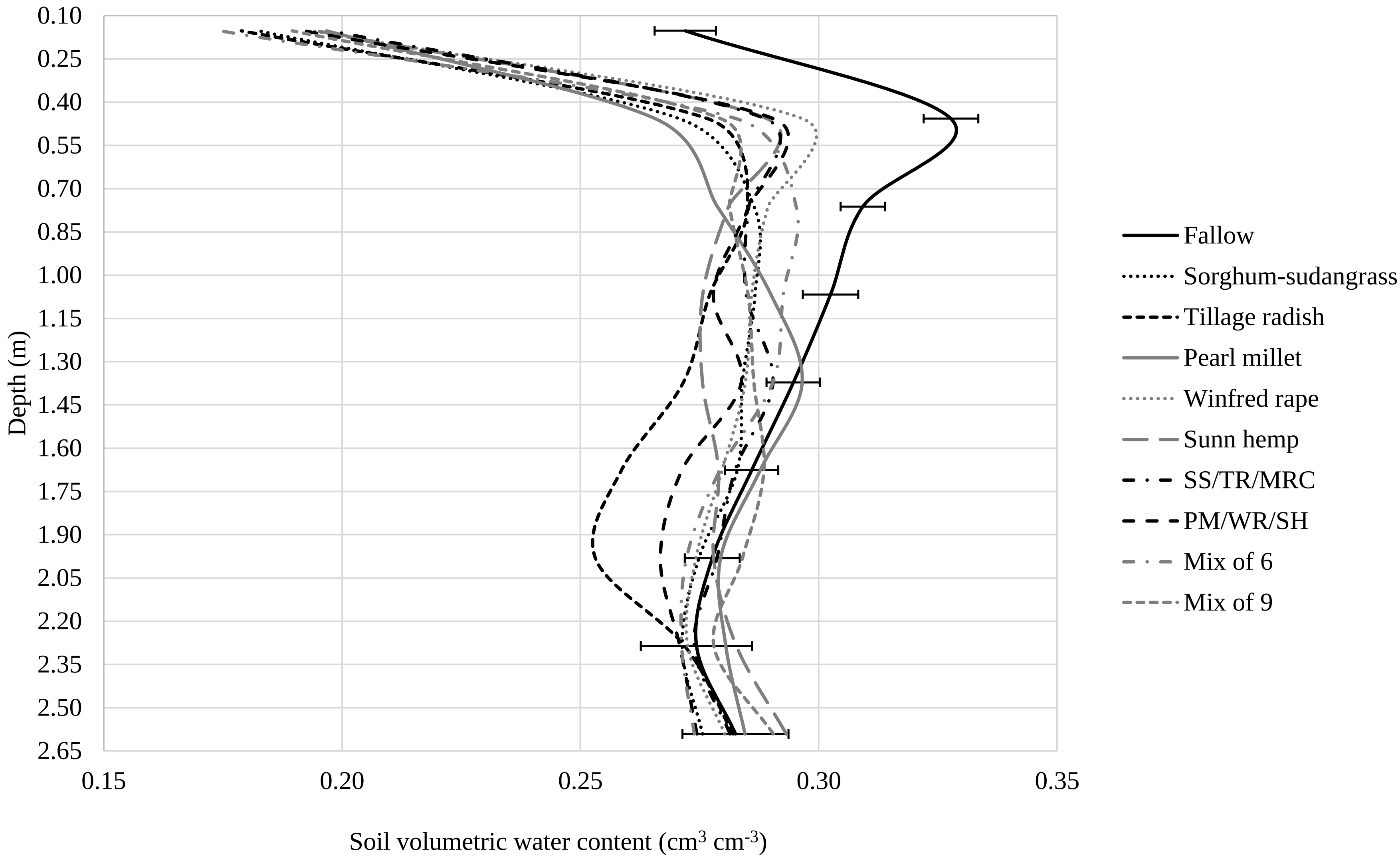

Figure 1.7 Soil volumetric water content to a depth of 2.59 meters at Manhattan, 18 September 2014, cover crop termination.

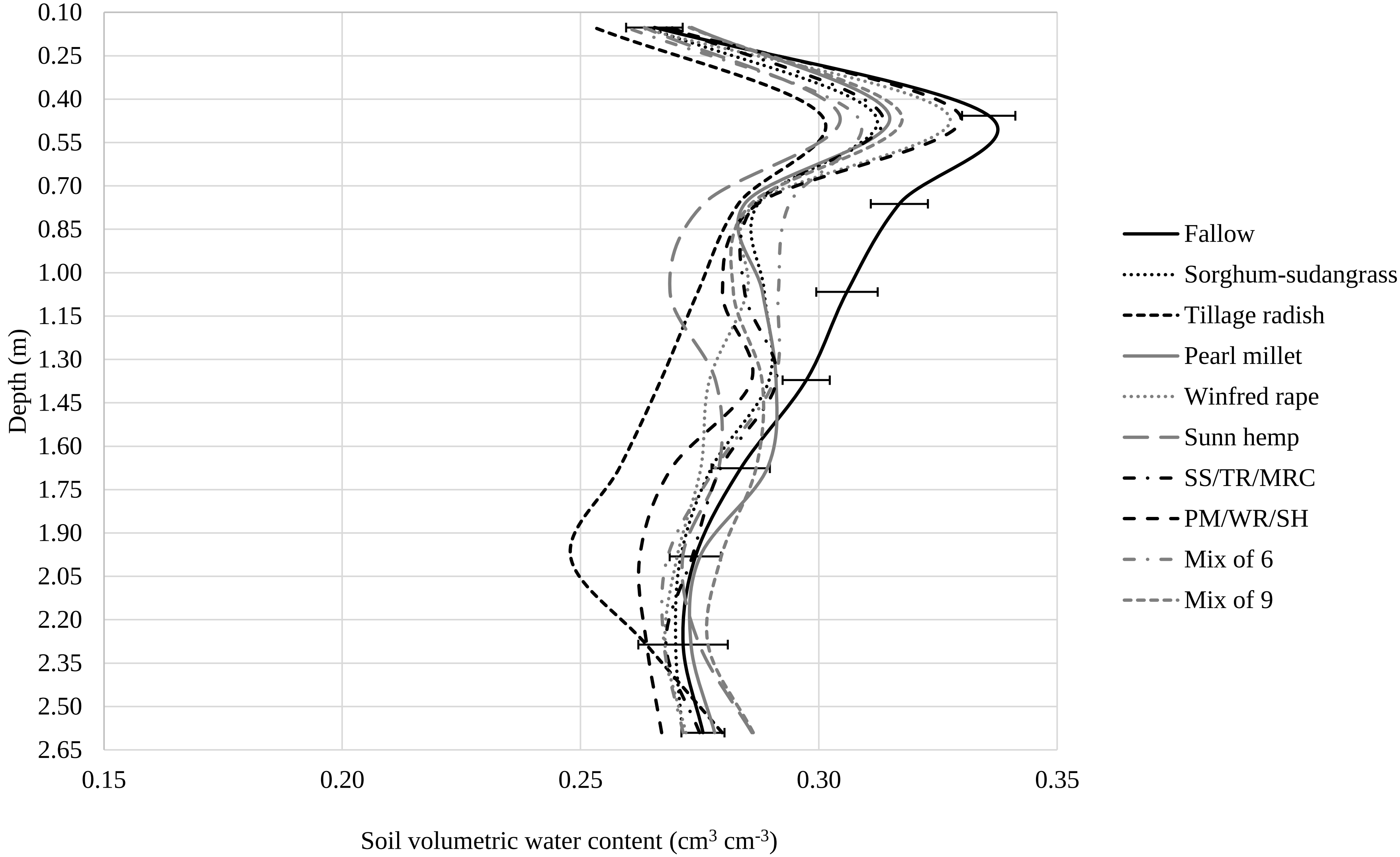

Figure 1.8 Soil volumetric water content to a depth of 2.59 meters at Manhattan, 24 January 2014, final reading.

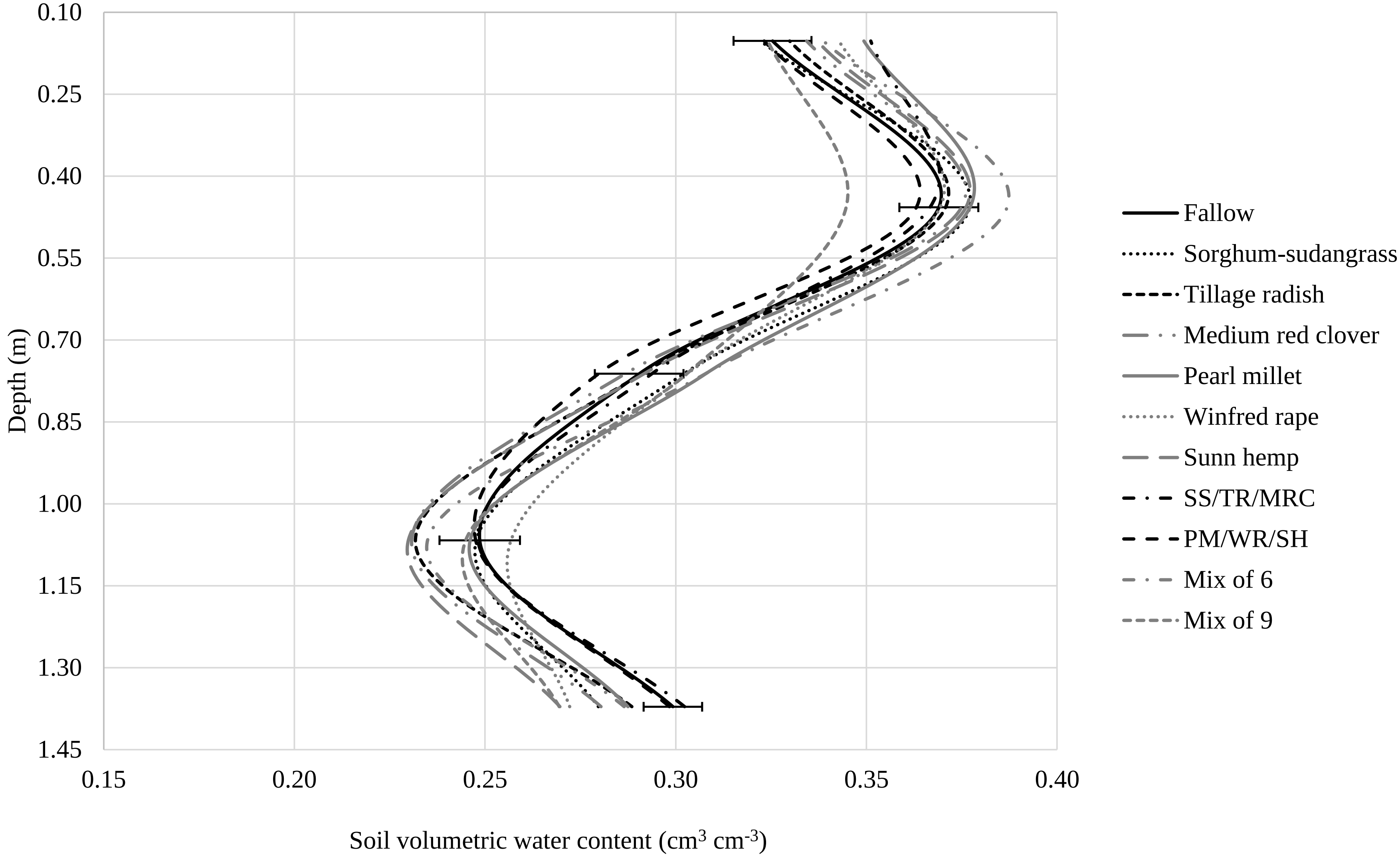

Figure 1.9 Soil volumetric water content to a depth of 1.37 meters at Belleville, 18 August 2013, early cover crop growth.

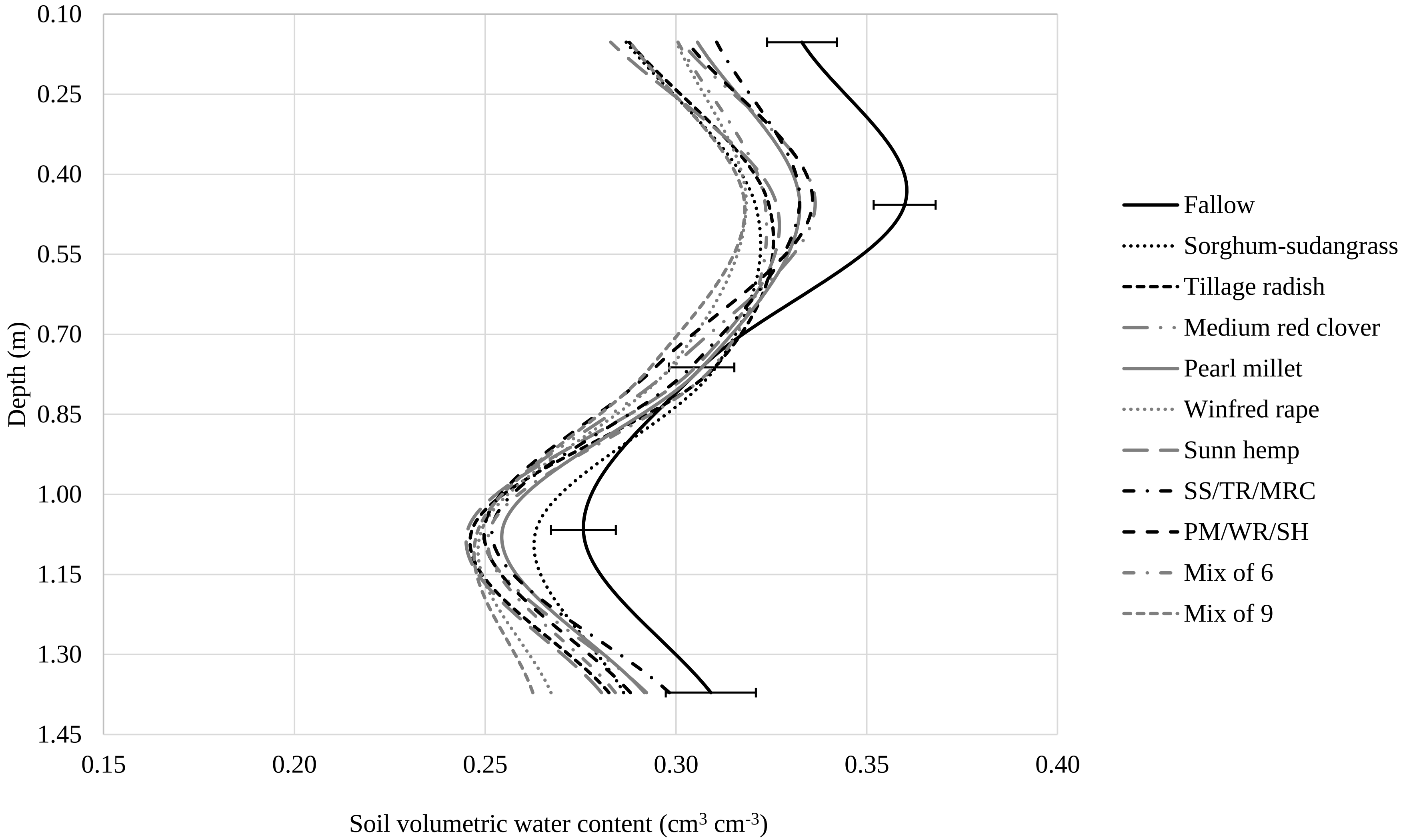

Figure 1.10 Soil volumetric water content to a depth of 1.37 meters at Belleville, 10 November 2013, cover crop termination.

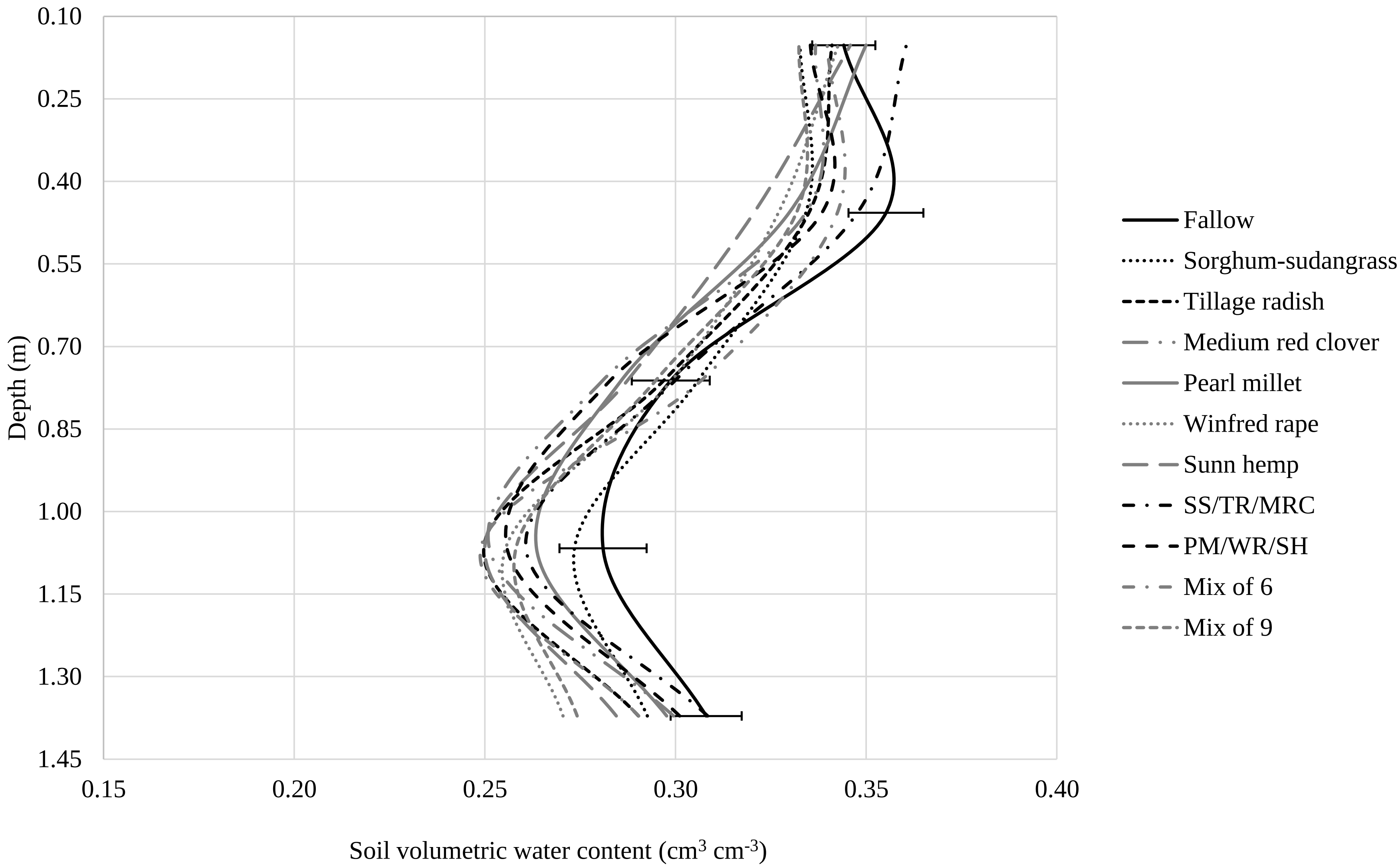

Figure 1.11 Soil volumetric water content to a depth of 1.37 meters at Belleville, 21 March 2014, final reading.

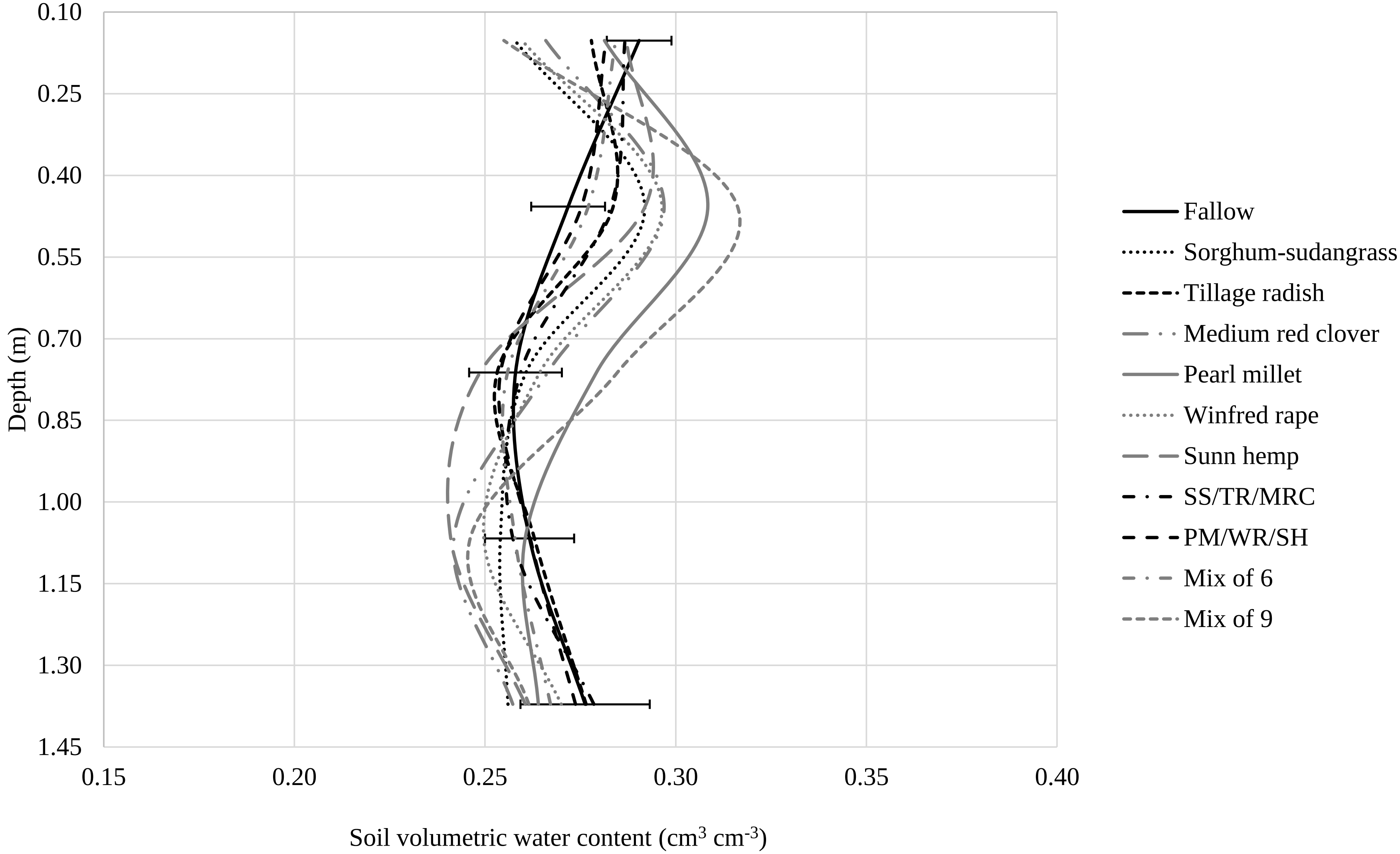

Figure 1.12 Soil volumetric water content to a depth of 1.37 meters at Belleville, 22 July 2014, early cover crop growth.

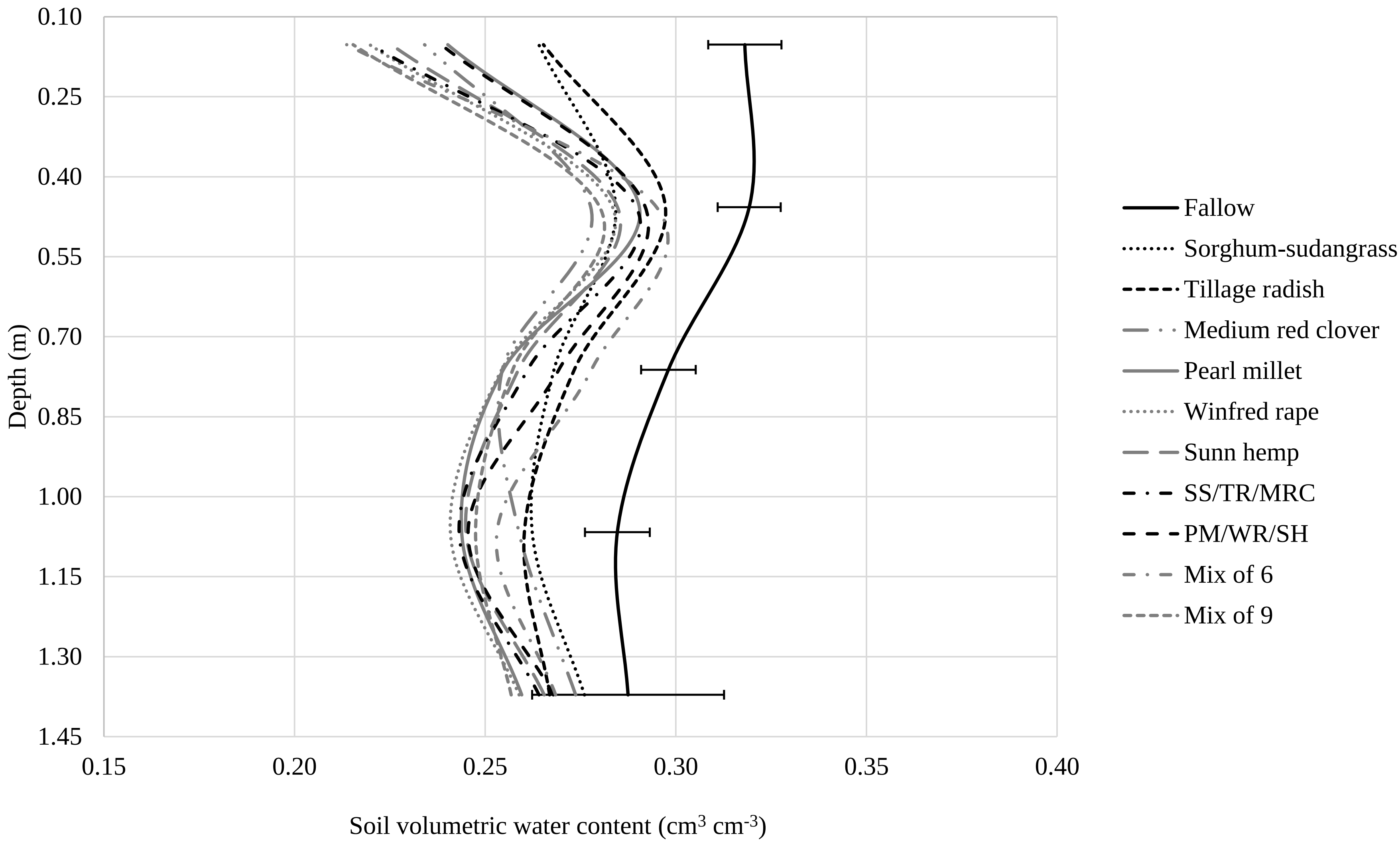

Figure 1.13 Soil volumetric water content to a depth of 1.37 meters at Belleville, 21 September 2014, cover crop termination.

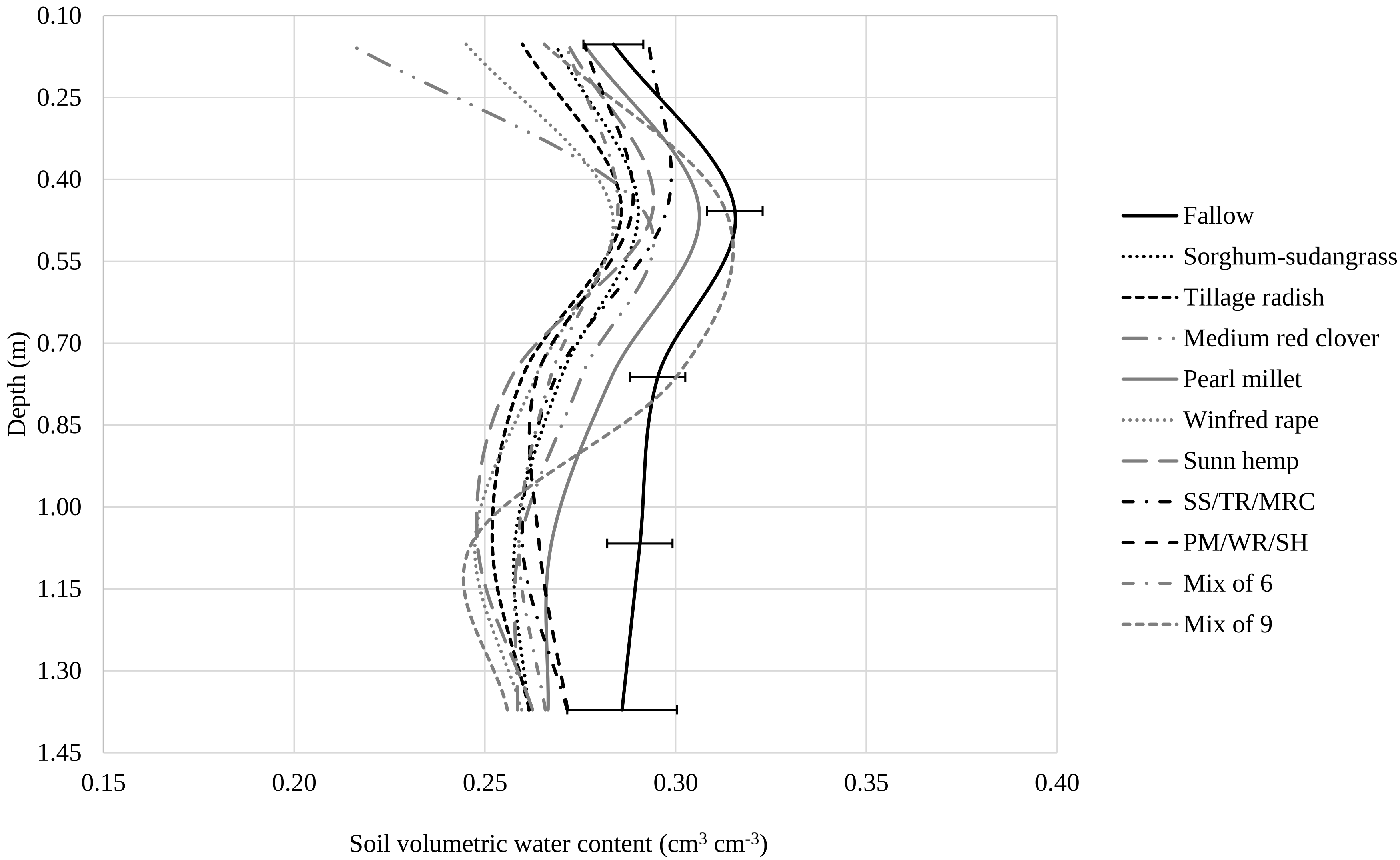

Figure 1.14 Soil volumetric water content to a depth of 1.37 meters at Belleville, 28 January 2015, final reading.

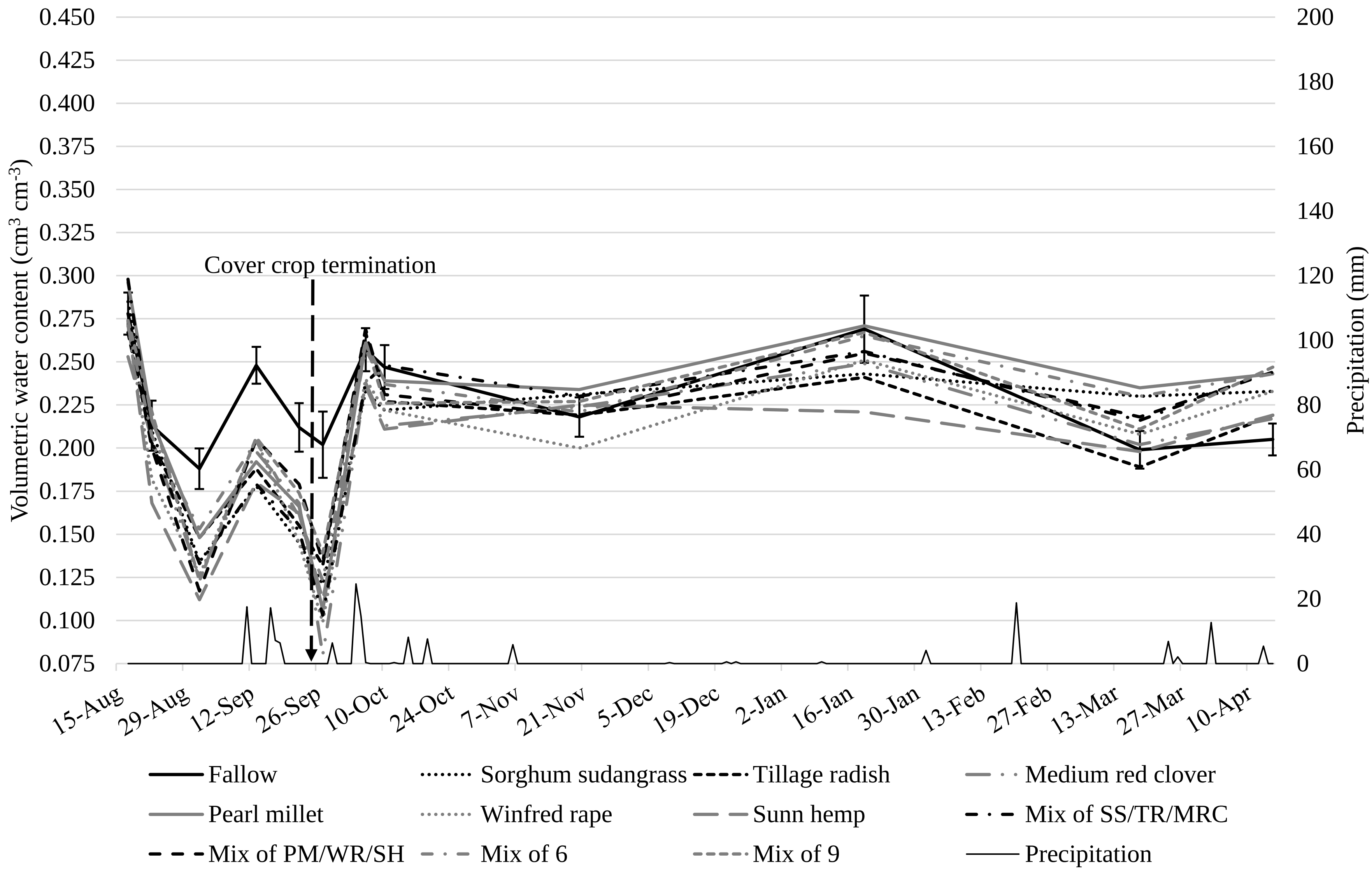

Figure 1.15 Actual precipitation and surface water content under single species cover crops and mixtures of increasing complexity at Manhattan 2013-14, before and after cover crop termination on 25 September.

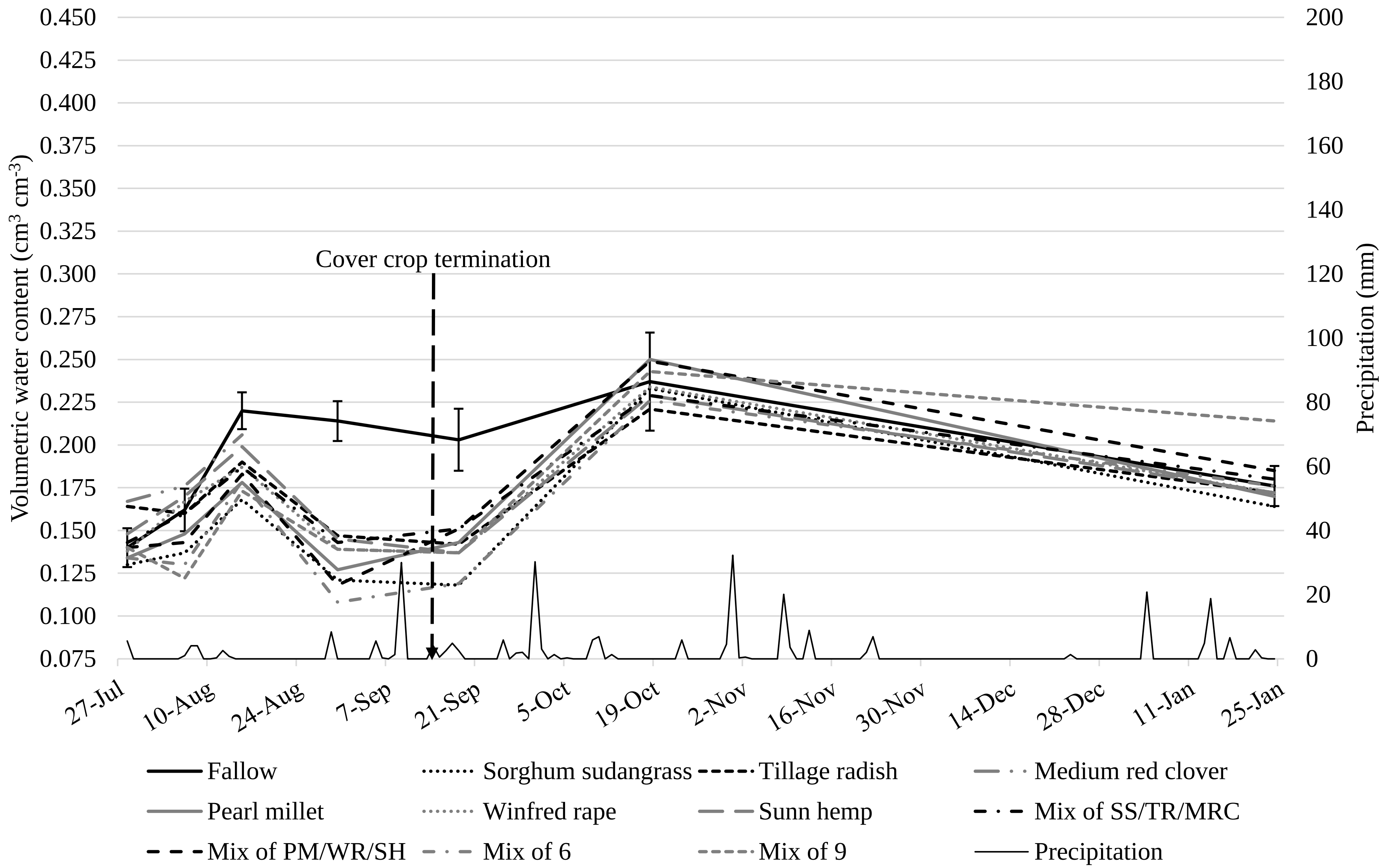

Figure 1.16 Actual precipitation and surface water content under single species cover crops and mixtures of increasing complexity at Manhattan 2014-15, before and after cover crop termination 16 September.

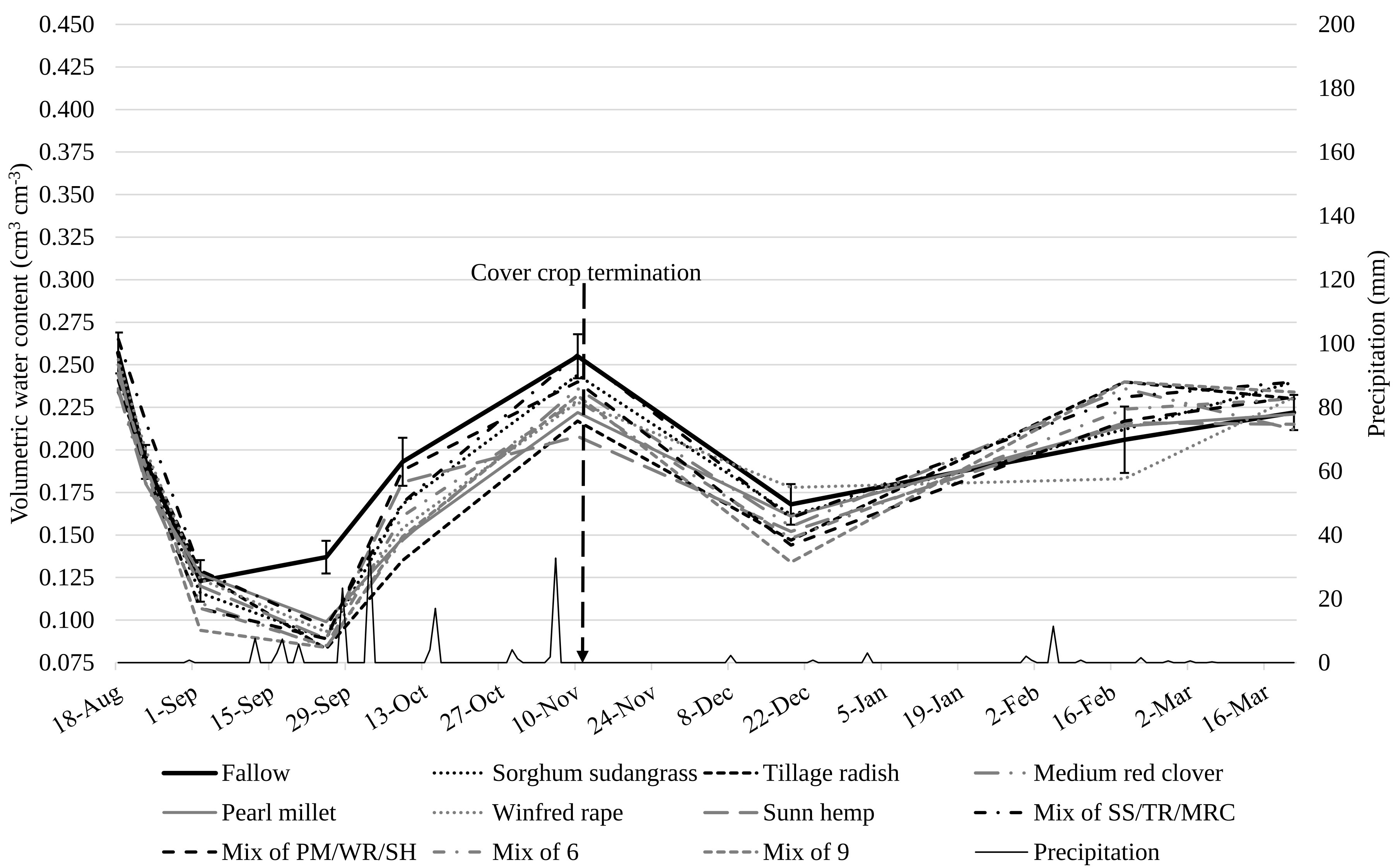

Figure 1.17 Actual precipitation and surface water content under single species cover crops and mixtures of increasing complexity at Belleville 2013-14, before and after cover crop termination 11 November.

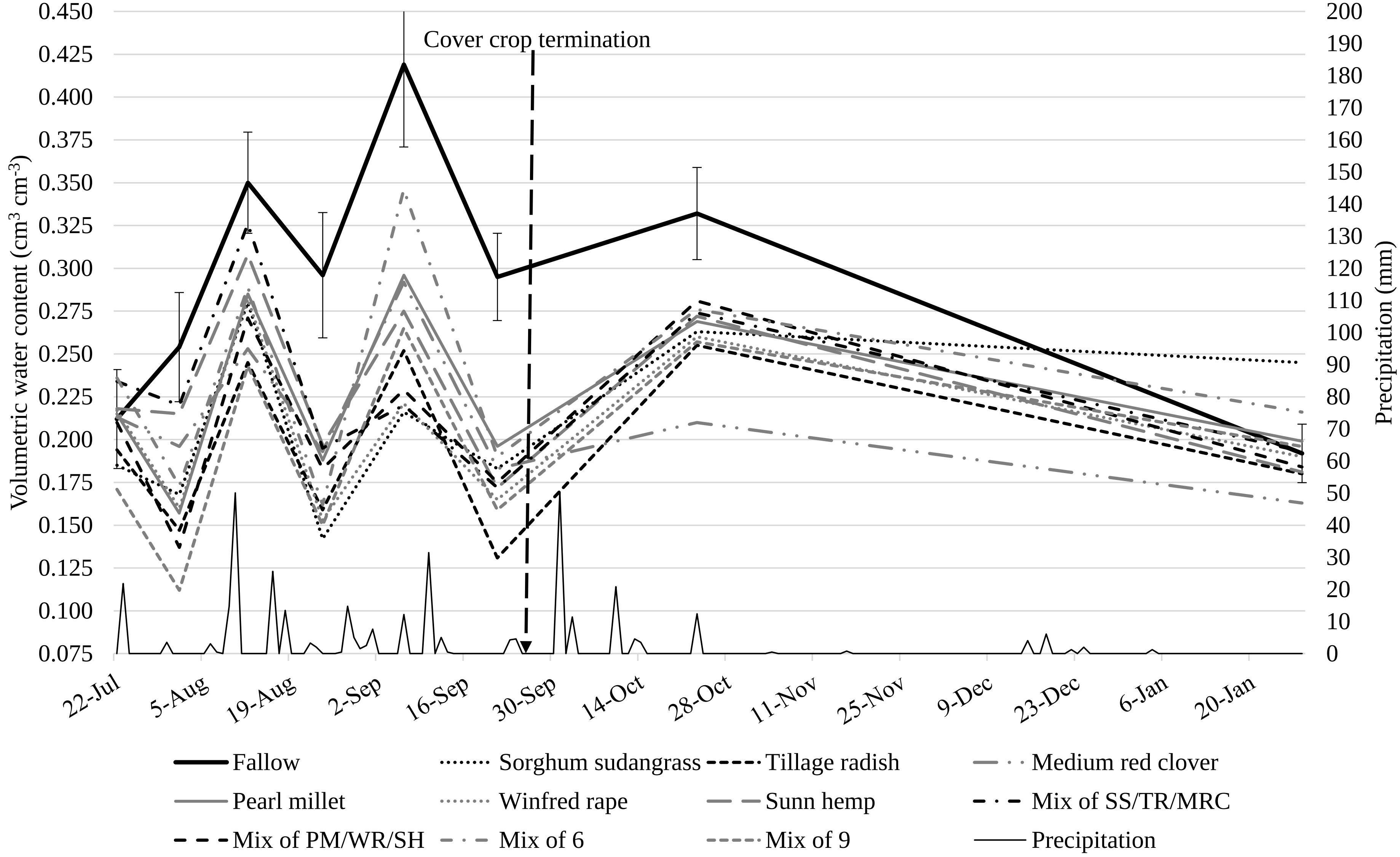

Figure 1.18 Actual precipitation and surface water content under single species cover crops and mixtures of increasing complexity at Belleville 2014-15, before and after cover crop termination 25 September.

Table 1.1 Species and seeding rates for cover crop treatments evaluated in experiments at Belleville and Manhattan, KS in 2013 and 2014.

Common name and abbreviation	Scientific name	Seeding rate			
		Single	Mix of 3	Mix of 6	Mix of 9
		kg ha^{-1}			
Grazex III Sorghum-sudangrass hybrid (SS)	*Sorghum bicolor* L. Moench	13.45	4.48ǂ	2.24	4.48
Pearl millet (PM)	*Pennisetum glaucum* L.	8.97	2.91†	1.46	2.24
Karakter tillage radish (TR)	*Raphanus sativus* L.	6.73	2.24ǂ	1.12	3.36
Winfred forage rape (WR)	*Brassica napus* L.	5.60	1.91†	0.93	3.36
Medium red clover (MRC)	*Trifolium pretense* L.	11.21	3.70ǂ	1.91	
Sunn hemp (SH)	*Crotalaria juncea* L.	13.45	4.48†	2.24	
Cowpea	*Vigna unguiculata* L. Walp.				3.36
Ethiopian cabbage	*Brassica carinata* A. Braun				3.36
Hairy vetch	*Vicia villosa* Roth				2.24
German millet	*Setaria italic*a L. P. Beauv.				2.24
Hunter forage turnip	*Brassica napus* L.				3.36

†Denote species in the Mix of PM/WR/SH.

ǂ Denote species in the Mix of SS/TR/MRC.

Table 1.2 Above-ground dry matter production and C:N ratios of cover crop species and mixtures of increasing complexity at all sites†.

	Dry matter				C:N			
Cover crop	Manhattan 2013	Belleville 2013	Manhattan 2014	Belleville 2014	Manhattan 2013	Belleville 2013	Manhattan 2014	Belleville 2014
	kg ha^{-1}				X:1			
Sorghum-sudangrass	7709 a	1902 ab	8969 a	7752 ab	60 a	48 a	32 ab	43 a
Pearl millet	4094 bc	1513 abc	8927 a	9236 a	51 ab	38 b	24 bcd	40 ab
Tillage radish	1917 ed	2020 ab	3518 a	4356 d	28 cd	14 d	14 e	23 de
Winfred rape	2416 cde	1484 bc	3702 a	3938 de	27 d	14 d	12 e	13 e
Medium red clover	876 e	1059 c	- -	2477 e	28 d	26 c	- -	22 de
Sunn hemp	2160 de	1017 c	4676 a	4902 cd	24 d	33 b	20 de	23 cde
Mix of SS/TR/MRC	4272 b	2025 ab	9893 a	6981 b	45 b	20 d	32 a	40 ab
Mix of PM/WR/SH	2963 bcd	2025 ab	9219 a	6456 bc	29 cd	17 d	23 cd	34 abc
Mix of 6	3316 bcd	2165 ab	8308 a	6531 bc	44 b	14 d	26 abcd	39 ab
Mix of 9	3629 bcd	2210 a	6002 a	4270 de	42 bc	17 d	28 abc	32 bcd

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 1.3 Carbon and nitrogen accumulation by cover crop species and mixtures of increasing complexity at all sites†.

Cover crop	Carbon accumulation								Nitrogen accumulation							
	Manhattan 2013		Belleville 2013		Manhattan 2014		Belleville 2014		Manhattan 2013		Belleville 2013		Manhattan 2014		Belleville 2014	
	kg ha^{-1}															
Sorghum-sudangrass	3256	a	805	ab	3963	a	3230	ab	54	a	17	b	127	ab	84	abc
Pearl millet	1705	b	636	abc	3757	ab	3715	a	33	b	17	b	174	a	98	a
Tillage radish	746	de	802	ab	1405	c	1687	de	27	bc	57	a	115	ab	107	a
Winfred rape	962	cde	582	bc	1484	c	1491	de	37	b	45	a	121	ab	114	a
Medium red clover	368	e	445	c	-	-	1027	e	13	c	19	b	-	-	50	c
Sunn hemp	911	cde	412	c	2127	bc	2048	cd	39	ab	12	b	111	ab	93	ab
Mix of SS/TR/MRC	1764	b	813	ab	4343	a	2847	b	40	ab	44	a	140	ab	79	abc
Mix of PM/WR/SH	1207	bcd	821	ab	3956	a	2554	bc	42	ab	49	a	165	ab	80	abc
Mix of 6	1365	bcd	863	a	3623	ab	2659	bc	32	b	63	a	144	ab	77	abc
Mix of 9	1484	bc	866	a	2594	abc	1685	de	37	b	51	a	97	b	54	bc

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 1.4 Water loss at Manhattan in 2013-15 during cover crop growth, from cover crop termination to final reading, and total†.

Treatment	Manhattan 2013-14 During growth 17 Aug to 22 Sept		Manhattan 2013-14 Termination to final 22 Sept to 15 Apr		Manhattan 2013-14 Total 17 Aug to 15 Apr		Manhattan 2014-15 During growth 28 July to 18 Sept		Manhattan 2014-15 Termination to final 18 Sept to 24 Jan		Manhattan 2014-15 Total 28 July to 24 Jan	
	cm											
Fallow	2.9	c	10.0	a	12.8	d	18.0	e	7.2	a	25.2	e
Sorghum-sudangrass	13.4	ab	4.6	cd	18.0	abc	20.0	cde	5.7	b	25.8	cde
Pearl millet	12.4	ab	4.4	d	16.8	bc	21.6	abcd	6.2	b	27.9	abc
Tillage radish	14.5	a	6.6	b	21.1	a	23.7	a	6.1	b	29.7	a
Winfred rape	13.1	ab	6.4	bc	19.5	ab	18.0	e	7.2	a	25.2	e
Medium red clover	10.8	b	4.9	bcd	15.7	cd	19.5	cde	5.8	b	25.3	de
Sunn hemp	14.0	a	5.3	bcd	19.2	ab	23.2	ab	6.3	b	29.5	ab
Mix of SS/TR/MRC	12.7	ab	3.5	d	16.2	bcd	21.3	abcd	6.4	ab	27.7	abcd
Mix of PM/WR/SH	12.9	ab	4.7	cd	17.6	bc	21.1	bcd	6.0	b	27.1	bcde
Mix of 6	12.2	ab	4.3	d	16.5	bc	19.3	de	6.5	ab	25.8	cde
Mix of 9	12.9	ab	5.3	bcd	18.2	abc	21.8	abc	5.7	b	27.5	abcde

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 1.5 Water loss at Belleville in 2014-15 during CC growth, from CC termination to final reading, and total†.

	Belleville 2013-14						Belleville 2014-15					
Treatment	During growth 18 Aug to 10 Nov		Termination to spring 10 Nov to 21 Mar		Total 18 Aug to 21 Mar		During growth 22 July to 21 Sept		Winter water loss 21 Sept to 28 Jan		Total 22 July to 28 Jan	
	cm											
Fallow	12.9	c	2.3	a	15.3	b	27.7	d	3.7	a	31.3	d
Sorghum-sudangrass	16.4	ab	0.2	cd	16.6	ab	31.7	bc	2.2	ab	33.9	c
Pearl millet	16.9	ab	1.3	abc	18.2	ab	31.5	bc	3.1	a	34.6	abc
Tillage radish	16.4	ab	0.5	bcd	16.9	ab	32.7	abc	3.2	a	35.9	ab
Winfred rape	17.9	a	0.0	cd	19.1	a	34.9	a	1.2	b	36.0	ab
Medium red clover	15.4	bc	1.7	ab	17.1	ab	33.5	ab	2.7	ab	36.2	a
Sunn hemp	16.5	ab	0.9	bcd	17.4	ab	31.9	bc	2.7	ab	34.7	abc
Mix of SS/TR/MRC	16.5	ab	-0.1	cd	16.5	ab	31.7	bc	2.5	ab	34.1	bc
Mix of PM/WR/SH	15.8	ab	1.1	abcd	16.9	ab	31.0	c	3.3	a	34.2	bc
Mix of 6	17.1	ab	0.6	bcd	17.7	ab	31.6	bc	3.0	a	34.6	abc
Mix of 9	16.9	ab	-0.1	d	16.8	ab	32.0	bc	2.7	ab	34.7	abc

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 1.6 Amount of biomass produced per input of water for cover crop treatments evaluated in four experiments in KS in 2013 and 2014†.

Treatment	Manhattan 2013		Manhattan 2014		Belleville 2013		Belleville 2014	
	kg ha^{-1} cm^{-1}							
Sorghum-sudangrass	618	a	447	a	115	abc	245	ab
Pearl millet	322	bc	457	a	90	abcd	294	a
Tillage radish	134	de	147	b	122	ab	133	de
Winfred rape	186	cde	170	b	80	bcd	114	de
Medium red clover	81	e	-	-	70	cd	74	e
Sunn hemp	155	de	202	b	63	d	153	cd
Mix of SS/TR/MRC	355	b	472	a	123	ab	238	ab
Mix of PM/WR/SH	233	bcde	428	a	135	a	209	bc
Mix of 6	274	bcd	431	a	126	ab	207	bc
Mix of 9	287	bcd	273	ab	131	a	128	de

†Values in a column followed by the same letter are not significantly different, α=0.05.

Chapter 2 - Effects of Double Crop and Cover Crops on Soil Water in an Established No-tillage Crop Rotation

Abstract

The addition of fallow replacements such as double-crop soybean and cover crops into no-till systems has become popular in Kansas in recent years as a means of increasing cropping system intensity and diversity. A primary concern of producers is the possibility that these fallow replacements may reduce the amount of soil water stored in the profile for the next grain crop, potentially reducing yields. Data were collected in 2014 from fallow, double-cropped soybean, and four types of cover crops planted after wheat harvest in a winter wheat-grain sorghum-soybean no-till cropping system established in 2007 near Manhattan, KS. The 2014 cover crop plantings were the third instance of these cover crop treatments on these plots with previous plantings occurring in 2011 and 2008 between the wheat and sorghum phases of the 3-yr rotation. Objectives were to evaluate the effect of cover crops and double-crop soybean on soil profile water content and water use efficiency. The cover crops were drilled on 3 July 2014 following wheat harvest, and summer cover crops were terminated with a roller/crimper on 16 September 2014. Tillage radish was killed by frost approximately 11 November 2014, and crimson clover winter killed in January or February 2015. Biomass was hand harvested from a one square meter area within each experimental unit. Harvest of double-crop soybeans occurred on 7 November 2014. Volumetric soil water content was measured to a depth of 1.37 m using a neutron probe and at the surface with a TDR 300. Sorghum-sudangrass produced the greatest amount of dry matter (6673 kg ha^{-1}) with the highest water use efficiency (250 kg cm^{-1}), though its residue had a high C:N ratio (39:1). During the summer, fallow exhibited the least water loss (10.2 cm). Sorghum-sudangrass and forage soybean had the least water loss in the fall (6.4 and

7.4 cm). During the winter, fallow showed the greatest water loss (5.5 cm). Double-crop soybean was one of the highest water using treatments overall (27.8 cm), whereas fallow exhibited the least water loss up to January (23.3 cm). Of all fallow replacements, sorghum-sudangrass produced the most biomass with the greatest efficiency, while also having the least impact on soil profile water content.

Introduction

In semiarid regions, the use of fallow to store water and stabilize crop rotations is common. Climate and precipitation patterns often determine the feasibility of replacing fallow in a crop rotation. With annual precipitation in Kansas ranging from 380 mm in the west to 915 mm in the east, effectiveness of these fallow replacement crops can vary (National Climatic Data Center, 2010). With precipitation storage efficiency during fallow generally ranging from ten to forty percent (Hansen et al., 2012), at least 60% of precipitation during fallow is therefore lost to evaporation, transpiration, leaching, or runoff (Stone, 2013). Around 75% of annual precipitation in the Great Plains is received from April through September (Farahani et al., 1998), though high temperatures from July to September accelerate evaporation and keep precipitation capture between 10-35% during this late fallow period (Peterson and Westfall, 2004).

The quantity of stored soil water during a fallow period is dependent on surface residue, soil type, soil restrictive layers, precipitation patterns, and duration of fallow, crop rotation, and tillage systems (Stone, 2013). With the addition of cover crops in no-till systems, cropping system intensity and diversity can be increased. The intensification of cropping systems can provide benefits such as greater water use efficiency, weed control, soil quality improvements, and fertility improvements (Leikam et al., 2007; McVay et al., 1989). By reducing the fraction of a cropping system in fallow, total biomass production of the complete rotation cycle can be increased (Aiken et al., 2013).

Cover crops serve as an alternative to fallow and are classified as any plant introduced during or directly after the main cropping phase of a system and terminated before the planting of the next crop (Hartwig and Ammon, 2002). The success of a cover crop often depends on their ability to suppress weeds, produce biomass, and increase soil organic matter, while not significantly decreasing soil water available for the subsequent grain crop (Schlegel and Havlin, 1997; Unger and Vigil, 1998). Cover crops also serve to protect the soil from wind and water erosion and increase the soil’s water holding capacity (Lu et al., 2000). To do this, they need to be easily established and terminated to produce adequate biomass and good soil cover.

Many classes of cover crops exist, and they are grown and managed to play a specific role in the cropping system. Legume cover crops may reduce or eliminate the nitrogen fertilizer requirement needed for the following cash crop because of their ability to fix atmospheric nitrogen (McVay et al., 1989). The availability of nitrogen from leguminous residues to subsequent crops can be affected by precipitation, temperature, length of growing season, soil type, and soil productivity (Vyn et al., 2000; Dekker et al., 1994; Stute and Posner, 1995). Leikam et al. (2007) reported that N fixation in leguminous species can provide up to 14 kg ha^{-1} of N to the next crop. Non-leguminous species such as sudangrass can provide nitrogen-trapping benefits, capturing nitrogen that might have otherwise leached from the rooting zone during a fallow period. Meisenger et al. (1990) found non-legume cover crops to be better at reducing soil nitrate leaching than legume cover crops or no cover crops. They are also effective for increasing soil organic nitrogen through increased biomass production (Kuo et al., 1997). Cool season cover crops can provide vegetative cover over winter, reducing wind and water erosion and also preventing nitrate leaching (Sainju and Singh, 2008). Brassicas in particular are excellent nutrient scavengers because of their extensive rooting network (Nanzyo et al., 2002).

A study by Janke et al. (2002) in south central Kansas found that cover crops could substitute for all or part of the nitrogen required for the next sorghum crop in years with adequate rainfall. In regions with precipitation less than 500 mm yr^{-1}, cover crops may reduce the available water for the subsequent crop even with increased water infiltration and improved soil properties (Schlegel and Havlin, 1997; Unger and Vigil, 1998; Reicosky and Forcella, 1998). Nielsen and Vigil (2005) found negative impacts on subsequent crop yields in years where precipitation was limiting. Management strategies such as termination timing and cover crop species selection require further investigation to reduce these negative impacts on soil water status.

When combined with a more water efficient cropping system, the addition of cover crops that produce large amounts of biomass should increase soil organic matter and surface residues, possibly resulting in increased stored soil moisture. Selection of cover crops that produce large amounts of biomass should include those that have efficient water use. In a no-tillage cropping system, the water increase in stored soil moisture might enable a low water use cover crop to be grown during the fallow period without reducing subsequent grain crops yield. Hao et al. (2014) found biomass yield and evapotranspiration (ET) to increase with increased water availability, though increased water did not affect water use efficiency (WUE). Biomass yield varied among years but ET was relatively stable, suggesting changes in WUE were due to increased biomass rather than reduced ET.

As another alternative to fallow, double-cropping soybeans after winter wheat has grown in popularity in regions of Kansas. According to the National Agricultural Statistics Service, 12-

13% of soybean acreage was planted following another harvested crop in 2012-2014 (NASS, 2014a). Double-cropped soybeans have a relatively low cost of inputs required to generate an additional crop harvest, with the greatest expense being the cost of seed. Overall, Kansas soybean yields ranged from 40.0 to 47.8 bushels acre^{-1} between 2010 and 2014, having the potential to improve cropping system revenues (NASS, 2014b). Cost of herbicide for double-cropped soybeans is similar to or less than that of fallow. Residue remaining on the field after soybean harvest is typically low however, hindering their potential benefits to soil health. Cropping systems that increase surface residue increase water use efficiency and fallow use efficiency (Nielsen et al., 2005). In a water efficient cropping system, adding cover crops that produce large quantities of biomass results in increased soil organic matter and further increases water storage (Lu et al., 2000). Crop residues protect the soil surface from the impact of raindrops and subsequent soil crusting, thus reducing runoff and increasing precipitation infiltration (Blanco-Canqui et al., 2011; Nielsen et al., 2005).

The date of cover crop termination can impact quantity of biomass produced and C:N ratio, and the method of termination can impact the effectiveness of a cover crop at controlling weeds and conserving water (Wagger, 1989; Lu et al., 2000). Cover crop termination methods include herbicide application, roller/crimpers, tillage, and mowing/chopping (Balkcom et al., 2007). Killing cover crops with an herbicide is a common method used by farmers in no-tillage systems because of the potential to cover many acres quickly. A drawback to herbicide termination is the potential to establish herbicide resistant weeds when using the same mode of action throughout the crop rotation (Culpepper et al., 2008). Roller/crimpers are a slower termination method, though usually an effective alternative to herbicides and tillage. They damage the plant by creating severe lodging and crimping of the stem, keeping the above ground part of the plant attached to the root system. This causes slower death and decomposition, but controls weeds for a longer period of time. Roller/crimpers work best with tall-growing cover crops and can create a more uniform mat that is easier to plant into than standing crops (Lu et al., 2000).

Cropping systems in the central Great Plains often include winter wheat and summer crops such as grain sorghum, corn, and soybean in wheat-fallow, wheat-summer crop-fallow, or wheat-summer crop rotations. High temperatures and variable precipitation throughout the growing season allow for the inclusion of double-cropped soybeans or cover crops into these crop rotations. Research is needed to identify how these rotations will respond to the water use of these incorporated fallow replacement crops. The objectives of this study were to quantify the change in soil water and biomass production of summer and winter legume and non-legume cover crop types, and the change in soil water under double-crop soybeans and chemical fallow in a no-tillage sorghum-soybean-winter wheat rotation in a precipitation regime of more than 500 mm annual rainfall. We hypothesized the change in soil water resulting from the fallow alternatives will be correlated to crop type and quantity of biomass produced.

Materials and Methods

Cover crop biomass production and change in soil water were evaluated in 2014 and 2015 for plots embedded in a field experiment initiated in 2007 to quantify the effects of cover crop types on a 3-yr, no-tillage crop rotation of winter wheat (*Triticum aestivum* L.) followed by a cover crop, grain sorghum [*Sorghum bicolor* (L.) Moench], and soybean (*Glycine max* L.). The experiment was located at the Kansas State University Department of Agronomy Ashland Bottoms Research Farm, 8 km south of Manhattan, KS (39°11'N 96°35'W) in an area mapped as moderately well drained Wymore silty clay loam (fine, smectitic, mesic Aquertic Argiudoll), with 0 to 1% slopes (Soil Survey Staff, 2015). The 30-yr mean annual precipitation for Manhattan is 905 mm, and average annual air temperature is 13°C (Figure 1.1; National Climatic Data Center, 2010). Treatments were evaluated in a randomized complete block design with four replications. Blocks were split by crop phase with each phase of the crop rotation present in each block every year. The rotational crop was randomized within each block. Split-blocks containing each rotational crop phase were 36 m wide by 68 m long, and the cover crop treatment plots were 6 m wide by 68 m long. Nitrogen in the form of 28% UAN was applied below the surface residue with a coulter applicator soon after grain sorghum emergence in 2009 and 2012.

Winter wheat (variety Everest) was drilled at a rate of 135 kg ha^{-1} in the fall of 2013, and 67 kg ha^{-1} 18-46-0 was applied with the seed. An additional 67 kg ha^{-1} nitrogen was applied in bands spaced 20 cm apart on 21 March 2014 as 28% UAN. Similar wheat management occurred in 2007 and 2010. Six cover crop treatments were established after harvest of winter wheat. Cover crop species were selected to represent the four primary crop types: summer legume, summer non-legume, winter legume, and winter non-legume. The summer non-legume was Grazex BMR sorghum-sudangrass [*Sorghum bicolor* L. Moench ssp. *drummondii*] and the summer legume was a late season forage soybean. Winter non-legume was Nitro tillage radish (*Raphanus sativus* L.) and the winter legume was crimson clover (*Trifolium incarnatum* L.). Species selection was based on ease of obtaining seed, seed cost, and popularity among producers. Chemical fallow was used as a control treatment, and double crop soybean was included as a common alternative to both fallow and cover crops in Kansas cropping systems.

Wheat stubble was sprayed with 1915.5 g ae ha^{-1} glyphosate and ammonium sulfate at 1120.85 g ha^{-1} to control volunteer wheat and weeds on 3 July 2014. All cover crops and double-crop soybeans were planted into the standing winter wheat stubble with a commercial no-till drill

(John Deere Model 1590, Deere & Co., Davenport, IA) on 3 July 2014. Glyphosate herbicide was applied to chemical fallow treatments throughout the summer to control weeds. Sorghum-sudangrass was drilled at a seeding rate of 25 kg ha^{-1}, double crop soybean (variety Asgrow 4033) and forage soybean (variety Stonewall) were drilled at a seeding rate of 395,000 seeds ha^{-1}, tillage radish (variety Nitro) 7.85 kg ha^{-1}, and crimson clover (variety not known) 22.42 kg ha^{-1}. All cover crops and double-crop soybeans were drilled on a 19-cm row spacing. The 2014 cover crop plantings were the third instance of these cover crop types on these plots with previous plantings occurring in 2011 and 2008 between the wheat and sorghum phases of the 3-yr rotation.

Summer cover crops (sorghum-sudan and forage soybean) were terminated on 16 September 2014 with a crop roller/crimper. Biomass was hand harvested from a one square meter area within each experimental unit. Sampling of sorghum-sudangrass and forage soybeans occurred on 11 September 2014, and tillage radish and crimson clover on 1 December 2014, although the tillage radish had been killed by frost approximately 11 November 2014. Sub-samples from each plot were dried in a forced-air dryer at 65°C, and then weighed to determine dry mass. Seed harvest of double-crop soybeans occurred on 7 November 2014.

Measurement of Soil Water

Soil moisture was tracked only in the 135 kg N ha^{-1} sub-plots, and was measured by neutron thermalization with a 503 DR Hydroprobe Moisture Gauge (CPN International, Inc., Martinez, CA) using a count duration of 16 s. Access tubes of standard type 6061-T6 aluminum tubing (o.d. 4.128 cm, wall thickness 0.089 cm) 1.83 m in length and to a depth of 1.68 m were installed on 15 July 2014. Starting at a depth of 0.152 m below the soil surface, water content was measured in 0.305 m increments to 1.37 m. A drop-hammer was used to drive the access tubes into holes made with a sampling tube (4.128 cm o.d., Giddings Machine Company, Inc., Windsor, CO) and tractor-mounted hydraulic probe (Model GSRTS, Giddings Machine Company, Inc.). Excess soil remaining in the tubes was removed with an auger and the tubes were covered at the top with a PVC cap. There was no seal at the base of tubes. The tubes were placed in the center of each plot in areas most representative of plot cover crop growth. Standard counts were recorded before and after tube measurements at each reading date. A mean standard count was used to calculate the count ratio (CR) from each tube-measured count (CR = measured count / mean standard count). The factory calibration equation ($\theta = 0.1733*CR - 0.006923$) of the neutron probe was used to calculate volumetric water content (θ). A field calibration for the neutron probe was in progress at the time of thesis submission. Soil water content was measured in each experimental unit bi-weekly during cover crop growth and monthly after termination. The soil water data, combined with daily precipitation records (recorded at a university weather station located within 0.50 km), were used to estimate cover crop evapotranspiration (ET) in each plot by the water balance method, assuming runoff and deep percolation to be negligible. Field conditions suggested runoff was indeed negligible, as there were no signs of soil or residue movement. The Wymore soil type is classified as having insignificant leaching losses, implying drainage through the soil profile would be unlikely (Kissel et al., 1982).

Surface soil moisture was measured using a Field Scout TDR 300 Soil Moisture Meter (rod length 12 cm, Spectrum Technologies, Inc., Plainfield, IL). Readings were taken on the same dates as neutron probe readings, with one reading per plot. The TDR 300 was calibrated to Manhattan's Wymore silty clay loam by wetting soil samples to known water contents. A 0.005 M calcium sulfate solution was used to wet the soil to minimize clay dispersion. Moistened soil was packed into PVC columns (10.2 cm i.d. and 16.5 cm height) using five lifts, each 3-cm in height. Three replicates of four moisture contents were utilized. TDR 300 period readings were taken from each column after packing, as well as gravimetric samples. A calibration equation of (θ = Period*0.000214-0.412) with an R^2 = 0.993 and RMSE = 0.0129 $cm^3\ cm^{-3}$ was thus generated. Benor et al. (2012) also found a strong linear relationship between TDR 300 output expressed in the meter's period reading and the volumetric water content of a soil.

Statistical Analyses of Data

Analysis of variance was conducted using the GLIMMIX procedure (SAS Institute, 2004) to determine significance of treatment factors with cover crop treatments as fixed effects and replications as random effects. Treatment means of response variables were separated using pair-wise t tests at $\alpha = 0.05$.

Results and Discussion

Dry Matter Productivity and Quality

Sorghum-sudangrass was the leading dry matter producer, producing almost double all other treatments (Table 2.1). Dry matter quantified for tillage radish was less than all other treatments, but may have been underestimated because of the time between the killing frost on 11 November and the sampling on 1 December.

Quality of dry matter was quantified with carbon and nitrogen accumulation and C:N ratios. Sorghum-sudangrass had the greatest carbon accumulation, and forage soybean showed the greatest nitrogen accumulation (Table 2.2). Tillage radish had the least amount of carbon and nitrogen accumulation among all treatments. Residue from forage soybean and crimson clover had the lowest C:N ratios of all treatments, both less than 20:1 (Table 2.1). To promote the timely decomposition of organic matter and subsequent release of nitrogen, a C:N ratio between 20:1 and 30:1 is desired (Allison, 1966; Kommendahl, 1984). One of the main reasons for combining legumes and non-legumes in mixtures is to achieve these lower C:N ratios (Creamer et al., 1997). Nitrogen accumulation by legumes through a symbiotic relationship with *Rhizobia* bacteria can also benefit non-legumes growing in mixtures through transfer of N by the roots (Giller et al., 1991). When growing a legume with a non-legume, the legume can accumulate more nitrogen than it would alone, as non-legumes will deplete soil nitrogen and foster increased biological nitrogen fixation by legumes to compensate (Ofori and Stern, 1987).

Change in Soil Water to Depth

Soil volumetric water content was measured to a depth of 1.37 m using a neutron probe. From the first neutron probe reading to summer termination, 118 mm of precipitation was received (Figure 1.1). Between summer and fall terminations, 85 mm of precipitation occurred, while there was 55 mm of rainfall between fall and winter terminations. At the time of sorghum-sudangrass and forage soybean termination on 16 September, all treatments exhibited water extraction throughout the profile except fallow, which appeared to store water in the surface 0.76 m (Figure 2.1). Compared to the initial reading on 21 July, water extraction of crimson clover was limited to the surface 0.5 m, and tillage radish showed substantial water extraction at the 1.37 m depth by the time of summer cover crop termination (Figure 2.1) that persisted until 26 January (Figure 2.2). All treatments except for crimson clover had started to regain moisture at the surface at termination of double-crop soybean and tillage radish on 10 November (Figure 2.2).

Throughout the summer and fall, fallow exhibited the least water loss, resulting in the least total water loss by 26 January (Table 2.3). During the fall period of 16 September to 10 November, crimson clover used the most water, as its production peaked later than the other treatments. Double-crop soybean was one of the greatest water losers during the summer period of 21 July to 16 September. It also ranked as a top water loser overall with forage soybean, crimson clover, and tillage radish. Sorghum-sudangrass used the most water in the summer during growth, then became the least water consumptive treatment in the fall (Table 2.3). Water use of the different fallow replacements varied across the summer, fall, and winter periods.

Water Use Efficiency

Sorghum-sudangrass was the most water use efficient during its growth phase and maintained this efficiency throughout the fall and winter even though it was no longer producing biomass (Table 2.4). As a summer annual C_4 plant, sorghum-sudangrass was able to more efficiently produce biomass in high temperatures than the cool season cover crops (Uliarte et al., 2012). Tillage radish and double-crop soybean exhibited the lowest water use efficiency throughout all phases (Table 2.4).

Surface Soil Water Content

Surface soil water content started out relatively equal for all treatments in July (Figure 2.3), but by 2 September plots in sorghum-sudangrass and tillage radish had less moisture at the surface than all other treatments. Between September and November, fallow began to acquire a moisture status similar to the fallow replacements. On 10 November, crimson clover had the driest soil at the surface, as it was still actively growing and using moisture. By the end of January, all treatments had reached similar surface water contents, as all treatments had either been terminated or become dormant (Figure 2.3).

Conclusions

Kansas' high temperatures and variable precipitation throughout summer months allow for the incorporation of double-cropped soybeans or cover crops into wheat-fallow and wheat-summer crop-fallow rotations (Norwood, 1999; Nielsen et al., 2005). In areas of Kansas with greater annual precipitation, year-to-year variability in precipitation amount and distribution can still cause a high degree of uncertainty in cropping system production. Previous studies in Kansas have suggested that cover crops might use too much soil water, reducing subsequent crop yields unacceptably, but the negative effects of cover crops were minimized with earlier termination dates (Schlegel and Havlin, 1997). System profitability and sustainability will need to be decided by the unique needs of the individual producer. Yield reductions may be acceptable to some if soil quality is improved long-term. The large selection of cover crops available to producers allows them to choose the species that best fits their crop rotation and individual needs at relatively low costs.

The purpose of this research was to quantify the change in soil water and biomass production of summer and winter legume and non-legume cover crop types, and the change in soil water under double-crop soybeans and chemical fallow in a no-tillage sorghum-soybean-winter wheat rotation in a precipitation regime of more than 500 mm annual rainfall. These potential fallow replacements can be integrated into current cropping systems to provide soil health benefits and increase overall cropping system sustainability.

Sorghum-sudangrass produced the greatest amount of dry matter (6673 kg ha^{-1}) with the highest water use efficiency (250 kg cm^{-1}), though its residue had a high C:N ratio (39:1). Double-crop soybean was one of the highest water using treatments (27.8 cm), whereas fallow exhibited the least water loss up to January (23.3 cm). By January, surface soil water contents had evened out between all treatments, indicating the final differences in water contents between treatments were due to extractions below 12 cm. Differences in extraction depths and efficiency of biomass production were linked to crop type.

References

Aiken, R.M., D.M. O'Brien, B.L. Olsen, and L. Murray. 2013. Replacing fallow with continuous cropping reduces crop water productivity of semiarid wheat. Agron. J. 105:199-207.

Allison, F.E. 1966. The fate of nitrogen applied to soils. Adv. Agron. 18:219-258.

Balkcom, K., H. Schomberg, W. Reeves, A. Clark. 2007. Managing cover crops in conservation tillage systems. In: Andy Clark, Managing cover crops profitably. Sustainable Agriculture Network, Beltsville, MD. 44-61.

Benor, M., G.J. Levy, Y. Mishael, and A. Nadler. 2012. Salinity effects on the Fieldscout TDR 300 soil moisture meter readings. Soil Sci. Soc. Am. J. 77:412-416.

Blanco-Canqui, H., M.M. Mikha, D.R. Presley, and M.M. Claasen. 2011. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Sci. Soc. Am. J. 75:1471-1482.

Creamer, N.J., M.A. Bennett, B.R. Stinner. 1997. Evaluation of cover crop mixtures for use in vegetable production systems. HortScience 32:866-870.

Culpepper, A.S., J.R. Whitaker, A.W. MacRae, and A.C. York. 2008. Distribution of glyphosate-resistant palmer amaranth in Georgia and North Carolina during 2005 and 2006. J. Cotton Sci. 12:306-310.

Dekker, A.M., A.J. Clark, J.J. Meisinger, F.R. Mulfor, and M.S. McIntock. 1994. Legume cover crop contributions to no-tillage corn production. Agron. J. 86:126-135.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil water storage in dryland cropping systems: the significance of cropping intensification. Soil Sci. Soc. Am. J. 62:984-991.

Giller, K.E., J. Ormesher, and F.M. Awah. 1991. Nitrogen transfer from *Phaseolus* bean to intercropped maize measured using ^{15}N-enrichement and ^{15}N-isotope dilution methods. Soil Biol. Biochem. 22:339-346.

Hansen, N.C., B.L. Allen, R.L. Baumhardt, and D.J. Lyon. 2012. Research achievements and adoption of no-till, dryland cropping in the semi-arid U.S. Great Plains. Field Crops Res. 132:196-203.

Hao, Baozhen, Q. Zue, B.W. Bean, W.L. Rooney, and J.D. Becker. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass Bioenerg. 62:108-116.

Hartwig, N.L., and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50:688-699.

Janke, R.R., M.M. Claassen, W.F. Heer, J. Jost, S. Freyenberger, and D.Norman. 2002. The use of winter annual legume cover crops in a wheat-grain sorghum rotation in south central

Kansas. Journal of Sustainable Ag. 20(2):69-88.

Kissel, D.E., O.W. Bidwell, and J.F. Kientz. 1982. Leaching classes of Kansas soils. Kansas Agricultural Experiment Station, Kansas State University. Bulletin 641.

Kommendahl, T. 1984. Interaction of nitrogen use and plant disease control, p. 561-474. In: R.D. Hauck (ed.). Nitrogen in crop production. ASA, CSA, SSSA, Madison, WI.

Kuo, S., U.M. Sainju, and E.J. Jellum. 1997. Winter cover cropping influence on nitrogen in soil. Soil Sci. Soc. Am. J. 61:1392-1399.

Leikam, D., R.E. Lamond, L.C. Banczkowski, J.S. Hickman, and D.A. Witney. 2007. Using legumes in crop rotations. L-778. Kansas State Extension Service, Manhattan, KS.

Lu, Y.C., A.A. Abdul-Baki, J.R. Teasdale, and K.B. Watkins. 2000. Cover crops in sustainable food production. Food Reviews International. 16:121-157.

McVay, K.A., D.E. Radcliffe, and W.L. Hargrove. 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. Soil Sci. Soc. Am. J. 53:1856-1862.

Meisinger, J.J., P.R. Shipley, and A.M. Decker. 1990. Using winter cover crops to recycle nitrogen and reduce leaching. In J.P Mueller and M.G. Wagger (ed.) Conservation tillage for agriculture in the 1990’s. Spec. Bull. 90-1. North Carolina State Univ., Raleigh, NC.

Nanzyo, M., Y. Shibata, and N. Wada. 2002. Complete contact of *brassica* roots with phosphorus fertilizer in a phosphorus-deficient soil. Soil Sci. Plant Nutr. 48(6):847-853.

National Climatic Data Center. 2010. 1981-2010 Normals. National Climatic Data Center, Asheville, NC.

National Agricultural Statistics Service. 2014. Acreage. [Online] Available at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1000/ (verified March 10, 2015).

National Agricultural Statistics Service. 2014. [Online] Available at http://quickstats.nass.usda.gov/results/70E45139-5E90-3981-AD01-932E3B1BB73F?pivot=short_desc (verified March 12, 2015).

Nielsen, D.C., and M.F. Vigil. 2005. Legume green fallow effect on soil water content and yield of winter wheat. Agron. J. 97:684-689.

Nielsen, D.C., P.W. Unger, and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97:364-372.

Norwood, C.A. 1999. Water use and yield of dryland row crops as affected by tillage. Agron. J. 91:108-115.

Ofori, C.F., and W.R. Stern. 1987. Cereal-legume intercropping systems. Adv. Agron. 26:177-204.

Peterson, G.A., and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144:127-138.

Reicosky, D.C., and F. Forcella. 1998. Cover crop and soil quality interaction in agroecosystems. J. Soil Water Conserv. 53:224-229.

SAS Institute. 2004. Release 9.1.3 ed. SAS Inst., Cary, NC.

Sainju, U.M., and B.P. Singh. 2008. Nitrogen storage with cover crops and nitrogen fertilization in tilled and non-tilled soils. Agron. J. 100:619-627.

Schlegel, A.J., and J.L. Havlin. 1997. Green fallow for the central Great Plains. Agron. J. 89: 762-767.

Soil Survey Staff. 2015. Web soil survey: Soil data mart. USDA-NRCS. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm (accessed 4 Mar. 2015).

Stone, L.R. 2013. Fallow efficiency: measuring the value of fallow. KSU agronomy e-Update 387. 1 Feb. 2013.

Stute, J.K., and J.L. Posner. 1995. Legume cover crops as a nitrogen source for corn in an oat-corn rotation. J. Prod. Agric. 8:385-390.

Uliarte, E.M., H.R. Schultz, C. Frings, M. Pfister, C.A. Parera, and R.F. del Monte. 2013. Seasonal dynamics of CO_2 balance and water consumption of C_3 and C_4-type cover crops compared to bare soil in a suitability study for their use in vineyards in Germany and Argentina. Agricultural and Forest Meteorology 181:1-16.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53:200-207.

Vyn, T.J., J.G. Faber, K.J. Janoviced, and E.G. Beauchamp. 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. 92:915-924.

Wagger, M.G. 1989. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. Agron. J. 81:533-538.

Figures and Tables

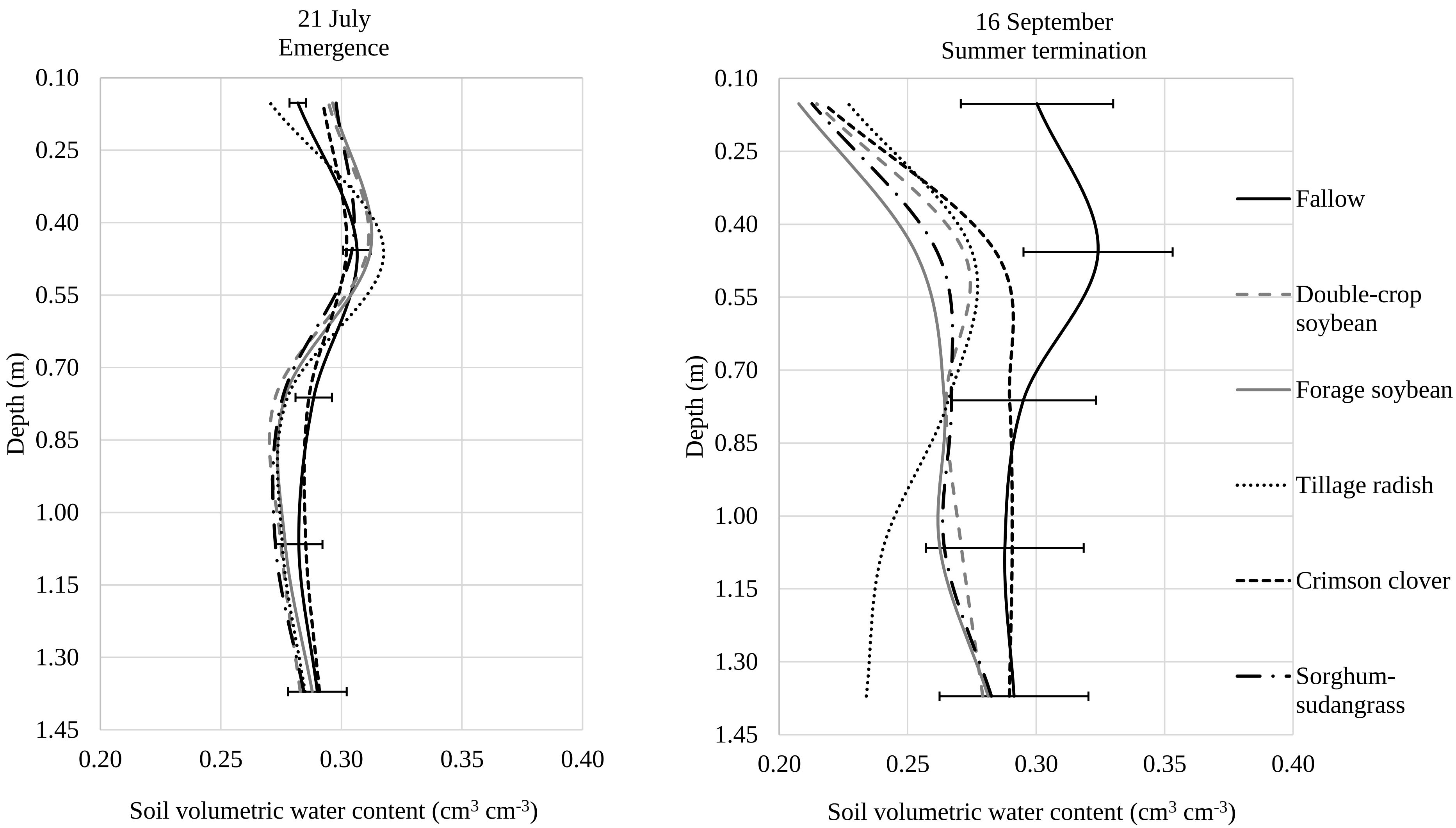

Figure 2.1 Soil volumetric water content to a depth of 1.37 meters under fallow, double-crop soybean, and cover crop treatments at emergence and summer termination.

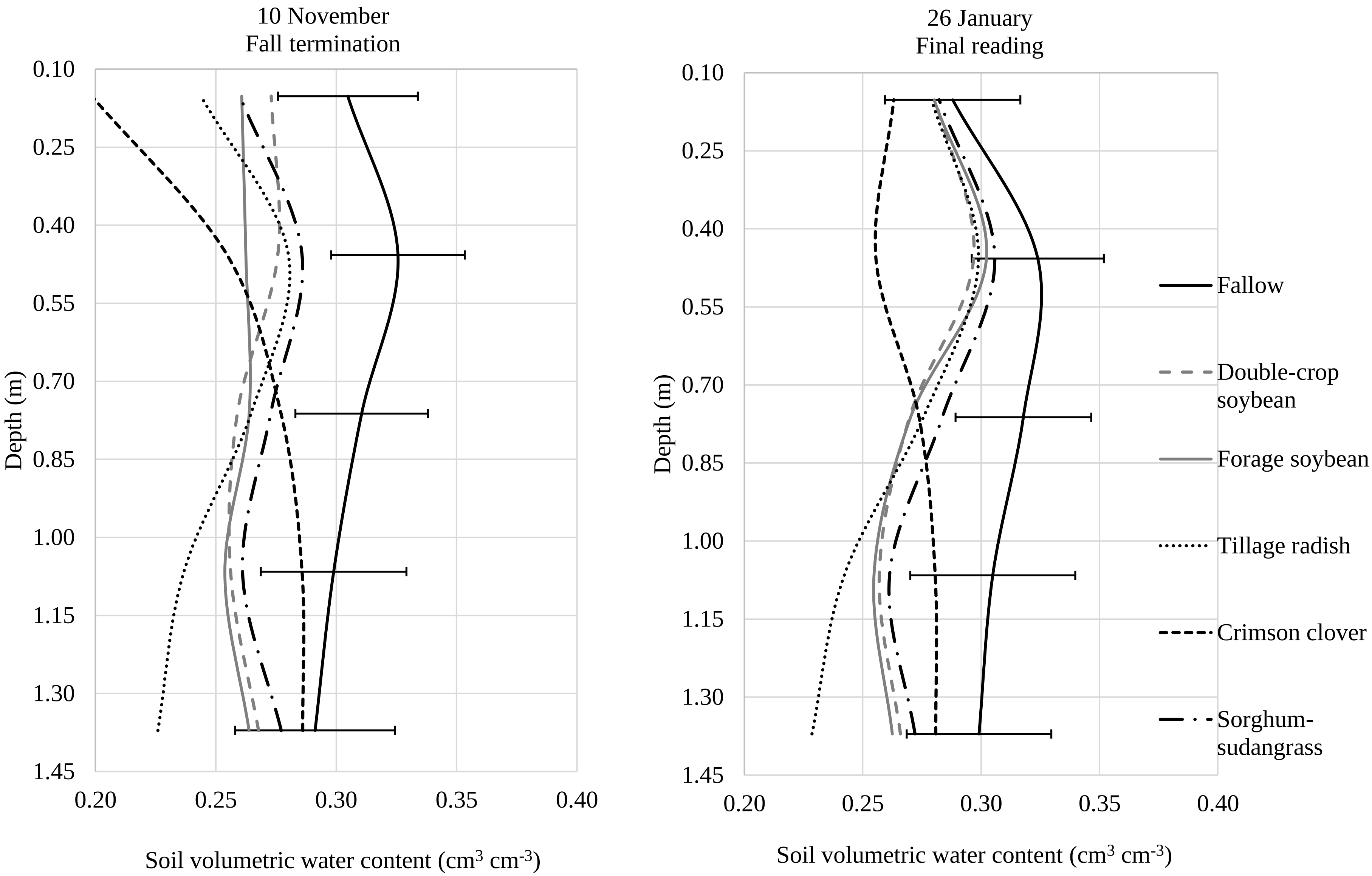

Figure 2.2 Soil volumetric water content to a depth of 1.37 meters under fallow, double-crop soybean, and cover crop treatments at fall termination and final reading.

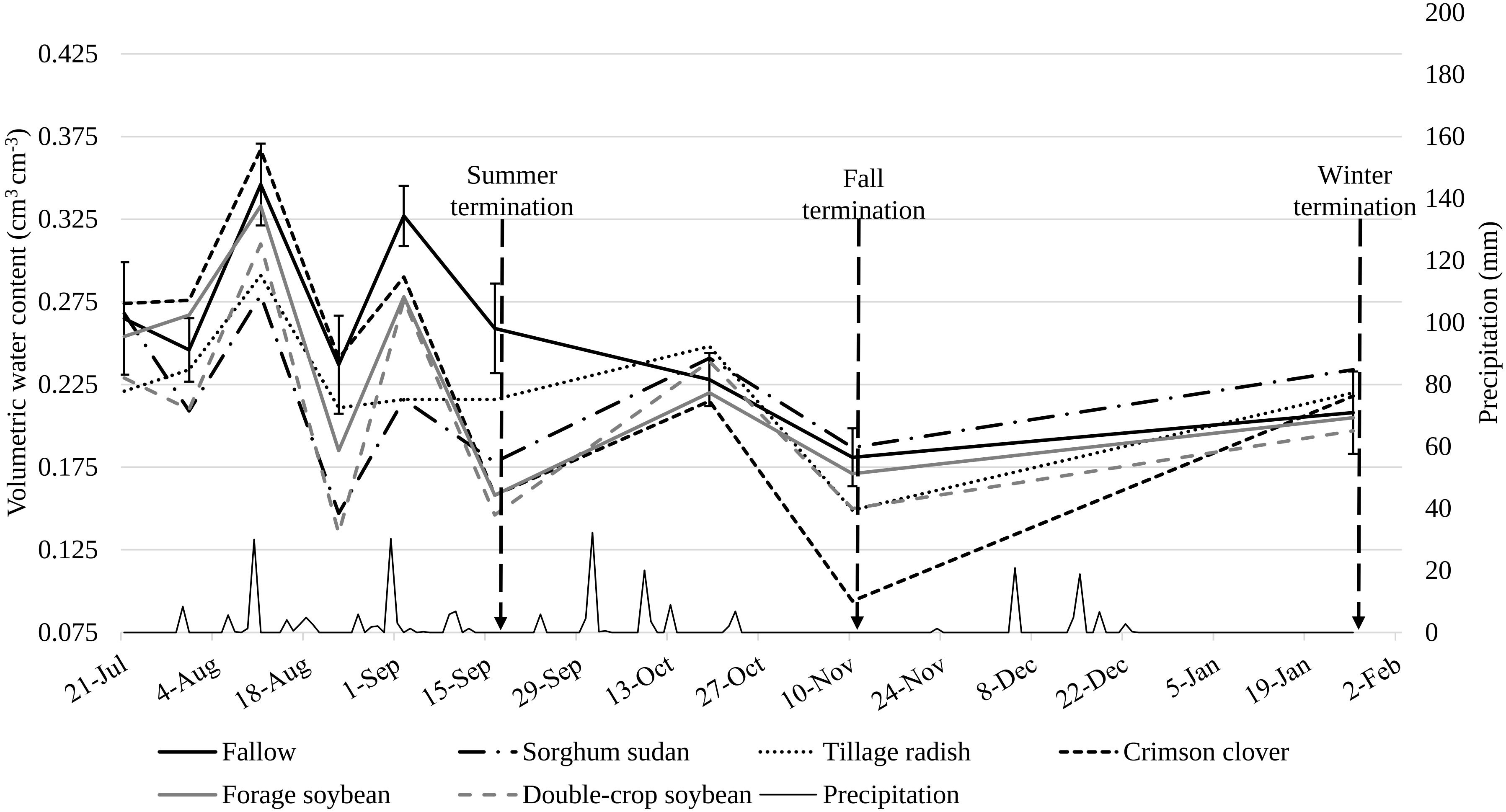

Figure 2.3 Actual precipitation and surface water content under fallow, cover crops, and double-crop soybean at Manhattan 2014-15 throughout summer termination 16 September, fall termination 10 November, and winter termination on 26 January.

Table 2.1 Dry matter production and C:N ratios of CC treatments.

Treatment	Dry Matter		C:N	
	kg ha^{-1}		X:1	
Sorghum-sudangrass	6673	a†	39	a
Forage soybean	3692	b	16	c
Crimson clover	3344	bc	18	c
Double-crop soybean	3288	bc	-	-
Tillage radish	2679	c	25	a

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 2.2 Carbon and nitrogen accumulation by cover crop species and mixtures of increasing complexity at all sites†.

Cover crop	Carbon accumulation		Nitrogen accumulation	
	kg ha^{-1}			
Sorghum-sudangrass	2815	a	75.72	b
Forage soybean	1571	b	99.84	a
Crimson clover	1421	b	78.98	b
Tillage radish	1025	c	42.00	c

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 2.3 Water loss during cover crop growth, from cover crop termination to final reading, and total†.

	Emergence to summer termination		Emergence to fall termination		Emergence to last moisture reading		Summer termination to fall termination		Winter water Loss	
	21 Jul to 16 Sep		21 Jul to 10 Nov		21 Jul to 26 Jan		16 Sep to 10 Nov		10 Nov to 26 Jan	
Treatment	cm									
Fallow	10.2	c	17.8	d	23.3	c	7.5	b	5.5	a
Sorghum-sudangrass	16.3	a	22.7	c	26.8	b	6.4	c	4.1	b
Forage soybean	17.6	a	24.7	ab	28.3	ab	7.4	bc	3.5	bc
Crimson clover	14.5	b	25.0	ab	29.0	a	10.6	a	4.0	bc
Double-crop soybean	15.9	ab	23.5	bc	27.8	ab	7.5	b	4.2	b
Tillage radish	17.4	a	25.6	a	29.0	a	8.2	b	3.3	c

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table 2.4 Water use efficiency of cover crops and double-crop soybean†.

Treatment	Summer WUE‡ 21 July to 16 Sept		Fall WUE 21 July to 10 Nov		Winter WUE 21 July to 26 Jan	
	kg ha^{-1} cm^{-1}					
Sorghum-sudangrass	411	a	295	a	250	a
Forage soybean	213	bc	150	b	131	b
Crimson clover	231	b	134	bc	115	bc
Double-crop soybean	211	bc	142	bc	120	bc
Tillage radish	153	c	104	c	92	c

†Values in a column followed by the same letter are not significantly different, α=0.05.
‡WUE calculated as total dry matter produced/cm water used within stated dates.

Appendix A - Raw Data

Table A.1 Cover crop biomass, water use, and nitrogen and carbon percentages. Data used to generate Tables 1.2-1.6.

Year	Location	Plot	Name	Dry Matter	CC WU	Total WU	Winter WU	N	C
				kg ha^{-1}	———	inches	———	—percent—	
2013	Manhattan	101	Mix of PM/WR/SH	2486	5.51	7.98	2.47	1.42	40.17
2013	Manhattan	102	Sunn Hemp	2599	5.95	8.01	2.06	1.91	41.28
2013	Manhattan	103	Tillage Radish	2651	5.57	8.45	2.88	1.43	38.50
2013	Manhattan	104	Fallow	.	1.22	6.21	4.99	.	.
2013	Manhattan	105	Mix of 9	3334	5.33	7.26	1.93	1.63	39.95
2013	Manhattan	106	Sorghum-sudangrass	6965	4.18	5.94	1.76	0.62	42.40
2013	Manhattan	107	Med. Red Clover	945	4.45	7.10	2.64	1.75	41.93
2013	Manhattan	108	Winfred Rape	2438	5.64	7.78	2.13	1.63	39.26
2013	Manhattan	109	Pearl Millet	2383	3.49	5.20	1.72	1.17	40.96
2013	Manhattan	110	6 singles	3557	4.97	6.64	1.67	0.78	40.33
2013	Manhattan	111	Mix of SS/TR/MRC	2398	5.98	6.38	0.40	1.13	40.98
2013	Manhattan	201	Tillage Radish	1094	6.32	8.92	2.60	1.64	38.74
2013	Manhattan	202	Sorghum-sudangrass	7539	5.26	7.45	2.18	0.72	42.07
2013	Manhattan	203	Mix of PM/WR/SH	2241	5.28	7.06	1.78	1.34	40.36
2013	Manhattan	204	Sunn Hemp	1628	5.61	8.19	2.59	1.72	43.57
2013	Manhattan	205	Med. Red Clover	425	4.11	5.32	1.21	1.45	41.94
2013	Manhattan	206	Pearl Millet	4343	4.57	6.43	1.86	0.85	42.14
2013	Manhattan	207	Winfred Rape	1983	5.21	8.26	3.05	2.13	39.82
2013	Manhattan	208	Mix of 9	3940	4.51	6.42	1.91	0.84	41.41
2013	Manhattan	209	Fallow	.	1.29	5.10	3.81	.	.
2013	Manhattan	210	Mix of SS/TR/MRC	2814	5.06	6.68	1.62	1.83	40.25
2013	Manhattan	211	6 singles	2476	5.24	6.82	1.58	0.84	41.72
2013	Manhattan	301	Winfred Rape	2100	4.73	7.12	2.39	1.11	40.36
2013	Manhattan	302	Pearl Millet	2936	5.37	7.28	1.91	0.64	41.64
2013	Manhattan	303	Fallow	.	1.01	4.61	3.60	.	.

2013	Manhattan	304	Tillage Radish	2248	5.70	8.30	2.60	1.41	38.57
2013	Manhattan	305	Mix of SS/TR/MRC	5245	3.89	6.18	2.29	0.63	41.47
2013	Manhattan	306	Sorghum-sudangrass	4759	6.99	9.15	2.16	0.98	42.07
2013	Manhattan	307	Mix of PM/WR/SH	3505	4.87	5.68	0.82	1.48	41.14
2013	Manhattan	308	Sunn Hemp	1914	4.75	6.81	2.06	1.72	41.06
2013	Manhattan	309	Med. Red Clover	1062	4.43	6.56	2.14	1.46	41.91
2013	Manhattan	310	Mix of 9	4269	6.72	9.27	2.55	0.84	41.22
2013	Manhattan	311	6 singles	3316	4.58	6.05	1.47	1.32	41.39
2013	Manhattan	401	Winfred Rape	3141	4.97	7.53	2.56	1.36	39.93
2013	Manhattan	402	Tillage Radish	1675	5.23	7.50	2.27	1.17	40.2
2013	Manhattan	403	Mix of PM/WR/SH	3618	4.67	6.98	2.31	1.39	41.02
2013	Manhattan	404	6 singles	3917	4.48	6.48	2.01	0.91	41.41
2013	Manhattan	405	Fallow	.	1.03	4.31	3.28	.	.
2013	Manhattan	406	Pearl Millet	6712	6.15	7.53	1.38	0.75	41.60
2013	Manhattan	407	Sorghum-sudangrass	11575	4.63	5.77	1.14	0.62	42.32
2013	Manhattan	408	Mix of 9	2973	3.78	5.78	2.00	0.87	40.80
2013	Manhattan	409	Med. Red Clover	1072	3.99	5.79	1.80	1.45	42.08
2013	Manhattan	410	Mix of SS/TR/MRC	6630	5.09	6.23	1.14	0.76	41.68
2013	Manhattan	411	Sunn Hemp	2499	5.67	7.29	1.63	1.80	43.00
2013	Belleville	501	Sorghum-sudangrass	2078	6.82	6.93	0.10	0.83	42.87
2013	Belleville	502	Mix of PM/WR/SH	1847	7.21	7.55	0.34	2.55	40.41
2013	Belleville	503	Mix of 9	1967	6.95	7.10	0.15	2.25	40.23
2013	Belleville	504	Winfred Rape	1879	8.25	8.74	0.49	3.26	38.23
2013	Belleville	505	Fallow	.	5.03	6.02	0.99	.	.
2013	Belleville	506	Mix of SS/TR/MRC	2248	6.22	6.11	-0.11	1.89	40.21
2013	Belleville	507	Sunn Hemp	673	6.32	6.63	0.31	1.41	42.13
2013	Belleville	508	6 singles	1665	6.61	6.86	0.25	2.90	40.33
2013	Belleville	509	Tillage Radish	2325	6.91	7.44	0.53	3.37	39.54
2013	Belleville	510	Pearl Millet	1312	7.14	7.64	0.50	1.19	42.07
2013	Belleville	511	Med. Red Clover	878	6.25	6.74	0.49	1.32	42.49
2013	Belleville	601	Mix of PM/WR/SH	2808	4.98	5.26	0.28	1.71	40.81
2013	Belleville	602	Winfred Rape	2258	7.64	7.53	-0.11	2.91	39.14

2013	Belleville	603	Sorghum-sudangrass	2621	6.75	6.99	0.24	0.77	42.06
2013	Belleville	604	Pearl Millet	1870	7.63	7.69	0.06	1.18	41.89
2013	Belleville	605	Fallow	.	5.57	6.35	0.78	.	.
2013	Belleville	606	Mix of SS/TR/MRC	2327	6.86	7.32	0.46	1.95	40.91
2013	Belleville	607	Med. Red Clover	1177	6.29	6.92	0.62	1.47	41.13
2013	Belleville	608	Tillage Radish	2961	6.61	6.47	-0.14	2.61	39.27
2013	Belleville	609	6 singles	3507	6.86	7.54	0.67	2.93	39.15
2013	Belleville	610	Mix of 9	2115	7.73	8.15	0.43	2.77	39.27
2013	Belleville	611	Sunn Hemp	1398	6.05	6.64	0.59	1.04	39.90
2013	Belleville	701	Sunn Hemp	372	7.13	7.27	0.14	1.64	42.46
2013	Belleville	702	Sorghum-sudangrass	1731	6.88	7.47	0.59	1.00	42.50
2013	Belleville	703	Med. Red Clover	617	6.16	6.73	0.57	1.65	41.89
2013	Belleville	704	Mix of PM/WR/SH	1843	6.02	6.67	0.65	3.24	40.36
2013	Belleville	705	Mix of SS/TR/MRC	1854	6.62	6.28	-0.35	3.20	39.45
2013	Belleville	706	Pearl Millet	1284	5.84	6.29	0.45	1.19	42.26
2013	Belleville	707	Mix of 9	1524	5.07	4.04	-1.03	2.77	39.53
2013	Belleville	708	Fallow	.	4.81	6.02	1.20	.	.
2013	Belleville	709	6 singles	2124	6.62	6.48	-0.14	3.25	39.89
2013	Belleville	710	Tillage Radish	1201	5.69	5.69	0.0026	2.84	39.68
2013	Belleville	711	Winfred Rape	967	6.75	6.35	-0.40	3.26	40.48
2013	Belleville	801	Mix of 9	3233	6.79	7.11	0.32	1.82	38.37
2013	Belleville	802	Pearl Millet	1585	5.95	7.00	1.05	0.90	42.11
2013	Belleville	803	Mix of PM/WR/SH	1602	6.63	7.09	0.46	2.60	40.33
2013	Belleville	804	Tillage Radish	1594	6.59	7.01	0.42	2.44	40.76
2013	Belleville	805	Mix of SS/TR/MRC	1670	6.31	6.21	-0.10	1.69	39.89
2013	Belleville	806	Winfred Rape	833	5.56	.	.	2.42	40.10
2013	Belleville	807	Sunn Hemp	1623	6.45	6.88	0.42	1.08	39.98
2013	Belleville	808	Fallow	.	4.98	5.65	0.66	.	.
2013	Belleville	809	Med. Red Clover	1562	5.54	6.48	0.95	2.38	42.41
2013	Belleville	810	6 singles	1364	6.90	7.04	0.14	2.37	41.10
2013	Belleville	811	Sorghum-sudangrass	1178	5.36	4.80	-0.56	1.01	41.65
2014	Manhattan	101	Sorghum-sudangrass	3745	5.42	9.14	3.72	1.51	44.78

2014	Manhattan	102	Pearl Millet	4269	5.34	8.93	3.59	2.90	41.58
2014	Manhattan	103	Mix of 9	4503	6.11	10.49	4.37	1.49	42.68
2014	Manhattan	104	6 singles	6837	5.53	10.04	4.51	1.68	43.65
2014	Manhattan	105	Sunn Hemp	4417	6.19	11.17	4.98	2.32	45.31
2014	Manhattan	106	Winfred Rape	4508	6.30	10.95	4.65	2.80	40.69
2014	Manhattan	107	Fallow	.	4.19	9.88	5.69	.	.
2014	Manhattan	108	Med. Red Clover	.	.	.	.	.	.
2014	Manhattan	109	Mix of SS/TR/MRC	13522	5.94	10.79	4.85	1.41	43.78
2014	Manhattan	110	Tillage Radish	4143	6.63	11.05	4.43	1.70	41.51
2014	Manhattan	111	Mix of PM/WR/SH	7766	6.10	10.39	4.29	1.74	42.66
2014	Manhattan	201	Tillage Radish	1785	5.84	10.42	4.58	4.10	38.30
2014	Manhattan	202	Mix of SS/TR/MRC	5370	6.51	11.37	4.85	1.13	45.16
2014	Manhattan	203	Mix of 9	6982	7.10	11.30	4.20	1.05	44.29
2014	Manhattan	204	6 singles	8760	5.71	10.02	4.30	1.40	44.82
2014	Manhattan	205	Mix of PM/WR/SH	14942	6.70	11.26	4.55	1.47	42.94
2014	Manhattan	206	Winfred Rape	2464	5.62	10.69	5.07	3.68	40.23
2014	Manhattan	207	Med. Red Clover	.	.	.	.	.	.
2014	Manhattan	208	Sunn Hemp	3899	6.73	11.42	4.69	2.18	45.53
2014	Manhattan	209	Fallow	.	4.22	10.18	5.95	.	.
2014	Manhattan	210	Sorghum-sudangrass	6913	6.30	11.14	4.83	1.25	45.06
2014	Manhattan	211	Pearl Millet	9112	5.70	10.26	4.56	1.21	42.75
2014	Manhattan	301	Tillage Radish	4020	6.93	11.73	4.80	4.01	38.12
2014	Manhattan	302	6 singles	9648	5.79	9.90	4.11	2.14	42.37
2014	Manhattan	303	Sorghum-sudangrass	11292	6.59	10.74	4.14	1.54	43.72
2014	Manhattan	304	Sunn Hemp	4454	7.39	12.40	5.01	2.17	45.47
2014	Manhattan	305	Mix of PM/WR/SH	9171	6.86	11.40	4.54	1.79	44.03
2014	Manhattan	306	Mix of SS/TR/MRC	10469	6.39	10.68	4.30	1.50	43.75
2014	Manhattan	307	Fallow	.	4.59	9.64	5.05	.	.
2014	Manhattan	308	Winfred Rape	4312	6.69	11.21	4.52	3.32	39.39
2014	Manhattan	309	Pearl Millet	7255	6.54	10.81	4.26	1.44	42.66
2014	Manhattan	310	Med. Red Clover	.	.	.	.	.	.
2014	Manhattan	311	Mix of 9	7678	7.22	10.87	3.65	1.80	43.35

2014	Manhattan	401	6 singles	7986	6.06	10.60	4.54	1.65	43.77
2014	Manhattan	402	Mix of PM/WR/SH	4997	5.74	9.67	3.93	2.82	41.20
2014	Manhattan	403	Tillage Radish	4126	8.81	13.64	4.82	3.71	40.83
2014	Manhattan	404	Fallow	.	4.52	9.95	5.43	.	.
2014	Manhattan	405	Sorghum-sudangrass	13925	5.73	9.58	3.85	1.36	43.97
2014	Manhattan	406	Winfred Rape	3526	6.35	11.01	4.66	3.54	40.01
2014	Manhattan	407	Mix of SS/TR/MRC	10210	6.39	10.81	4.42	1.48	43.55
2014	Manhattan	408	Pearl Millet	15071	5.33	9.87	4.54	2.37	41.54
2014	Manhattan	409	Mix of 9	4846	6.22	10.70	4.47	2.24	41.95
2014	Manhattan	410	Med. Red Clover	.	.	.	.	.	.
2014	Manhattan	411	Sunn Hemp	5935	6.62	11.49	4.88	2.70	45.59
2014	Belleville	501	6 singles	5885	8.38	13.38	5.00	0.64	40.93
2014	Belleville	502	Fallow	.	8.06	13.28	5.22	.	.
2014	Belleville	503	Pearl Millet	8371	8.58	13.26	4.68	0.82	39.82
2014	Belleville	504	Mix of 9	3705	8.93	13.30	4.37	0.92	39.06
2014	Belleville	505	Tillage Radish	3264	8.93	13.96	5.03	1.13	40.38
2014	Belleville	506	Med. Red Clover	1624	7.29	13.18	5.89	1.37	40.97
2014	Belleville	507	Sunn Hemp	4132	8.36	12.92	4.56	1.37	41.75
2014	Belleville	508	Sorghum-sudangrass	5466	8.75	13.51	4.77	0.70	41.37
2014	Belleville	509	Winfred Rape	3878	9.09	13.83	4.74	2.34	38.25
2014	Belleville	510	Mix of SS/TR/MRC	7480	8.46	13.04	4.58	0.64	41.14
2014	Belleville	511	Mix of PM/WR/SH	4894	8.90	13.82	4.92	1.01	39.17
2014	Belleville	601	Sunn Hemp	6115	9.12	13.68	4.56	2.27	41.03
2014	Belleville	602	Fallow	.	7.07	12.63	5.55	.	.
2014	Belleville	603	Mix of SS/TR/MRC	8080	7.65	13.29	5.63	1.23	40.70
2014	Belleville	604	Mix of PM/WR/SH	7207	8.69	13.37	4.68	0.93	39.36
2014	Belleville	605	Tillage Radish	3015	9.25	13.95	4.70	1.32	40.43
2014	Belleville	606	Pearl Millet	10772	8.71	13.43	4.73	1.12	40.51
2014	Belleville	607	Med. Red Clover	3253	8.79	14.48	5.69	1.79	41.42
2014	Belleville	608	Winfred Rape	3385	9.24	13.78	4.54	3.09	37.41
2014	Belleville	609	6 singles	5607	9.23	14.19	4.97	1.42	40.82
2014	Belleville	610	Mix of 9	2088	9.13	13.78	4.65	1.30	38.72

2014	Belleville	611	Sorghum-sudangrass	7855	8.69	12.96	4.28	0.82	41.97
2014	Belleville	701	Sunn Hemp	4701	9.35	13.44	4.09	1.80	42.61
2014	Belleville	702	6 singles	9102	8.64	13.00	4.36	1.10	41.00
2014	Belleville	703	Winfred Rape	3910	9.44	13.83	4.40	3.33	38.57
2014	Belleville	704	Mix of PM/WR/SH	6887	8.86	13.22	4.35	1.54	39.64
2014	Belleville	705	Sorghum-sudangrass	9140	9.14	13.79	4.65	1.23	41.35
2014	Belleville	706	Tillage Radish	5218	9.99	14.36	4.37	3.08	38.80
2014	Belleville	707	Med. Red Clover	2928	8.83	14.50	5.67	2.56	41.94
2014	Belleville	708	Mix of 9	4846	9.48	.	.	1.55	39.99
2014	Belleville	709	Mix of SS/TR/MRC	5530	9.10	.	.	1.85	40.05
2014	Belleville	710	Pearl Millet	7110	9.44	14.03	4.59	0.99	39.70
2014	Belleville	711	Fallow	.	5.99	11.57	5.58	.	.
2014	Belleville	801	6 singles	5532	9.35	13.92	4.57	1.65	39.91
2014	Belleville	802	Fallow	.	6.32	11.88	5.56	.	.
2014	Belleville	803	Sunn Hemp	4660	10.35	14.54	4.19	1.98	41.93
2014	Belleville	804	Sorghum-sudangrass	8547	9.06	13.18	4.12	1.43	41.90
2014	Belleville	805	Mix of PM/WR/SH	6837	9.35	13.52	4.17	1.44	39.95
2014	Belleville	806	Tillage Radish	5926	9.90	14.19	4.29	3.19	36.90
2014	Belleville	807	Winfred Rape	4581	11.35	15.32	3.98	2.81	37.28
2014	Belleville	808	Pearl Millet	10690	9.64	13.77	4.13	1.21	40.59
2014	Belleville	809	Mix of 9	6443	10.07	14.01	3.95	1.26	39.51
2014	Belleville	810	Med. Red Clover	2105	9.33	14.92	5.58	2.10	41.20
2014	Belleville	811	Mix of SS/TR/MRC	6833	9.86	14.02	4.15	1.00	41.09

Table A.2 Surface volumetric water contents. Data used to generate Figures 1.15-1.18

Site	Plot	Name	8/17/13	8/22/13	9/01/13	9/13/13	9/22/13	9/27/13	10/10/13	11/20/13	1/19/14	3/18/14	4/15/14
			$cm^3\ cm^{-3}$										
MHK‘13	101	PM/WR/SH	0.265	0.200	0.140	0.215	0.207	0.125	0.230	0.203	0.260	0.211	0.250
MHK‘13	102	SH	0.245	0.162	0.063	0.203	0.209	0.104	0.213	0.190	0.222	0.173	0.207
MHK‘13	103	TR	0.288	0.213	0.149	0.173	0.149	0.134	0.235	0.230	0.248	0.213	0.248
MHK‘13	104	Fallow	0.248	0.168	0.196	0.235	0.228	0.233	0.220	0.200	0.284	0.190	0.190
MHK‘13	105	Mix of 9	0.297	0.235	0.158	0.194	0.143	0.100	0.218	0.196	0.263	0.220	0.265
MHK‘13	106	SS	0.271	0.194	0.117	0.177	0.149	0.046	0.228	0.226	0.218	0.248	0.248
MHK‘13	107	MRC	0.252	0.192	0.123	0.226	0.183	0.128	0.215	0.233	0.245	0.209	0.248
MHK‘13	108	WR	0.239	0.209	0.121	0.213	0.140	0.029	0.241	0.237	0.256	0.233	0.271
MHK‘13	109	PM	0.333	0.228	0.136	0.192	0.228	0.104	0.260	0.233	0.295	0.271	0.248
MHK‘13	110	6 singles	0.254	0.198	0.160	0.200	0.175	0.093	0.213	0.218	0.314	0.243	0.226
MHK‘13	111	SS/TR/MRC	0.310	0.241	0.151	0.196	0.145	0.046	0.239	0.207	0.265	0.224	0.275
MHK‘13	201	TR	0.263	0.188	0.143	0.194	0.155	0.074	0.230	0.213	0.256	0.160	0.207
MHK‘13	202	SS	0.310	0.213	0.151	0.192	0.132	0.155	0.241	0.230	0.248	0.213	0.239
MHK‘13	203	PM/WR/SH	0.275	0.220	0.145	0.194	0.220	0.153	0.243	0.205	0.254	0.215	0.230
MHK‘13	204	SH	0.295	0.181	0.147	0.192	0.143	0.098	0.215	0.203	0.233	0.175	0.179
MHK‘13	205	MRC	0.288	0.181	0.134	0.177	0.158	0.029	0.222	0.205	0.254	0.185	0.173
MHK‘13	206	PM	0.284	0.228	0.140	0.200	0.190	0.078	0.235	0.239	0.260	0.222	0.245
MHK‘13	207	WR	0.282	0.198	0.145	0.248	0.164	0.110	0.235	0.200	0.252	0.209	0.215
MHK‘13	208	Mix of 9	0.299	0.203	0.128	0.228	0.218	0.209	0.271	0.235	0.271	0.213	0.252
MHK‘13	209	Fallow	0.314	0.267	0.170	0.260	0.190	0.200	0.218	0.224	0.303	0.192	0.222
MHK‘13	210	SS/TR/MRC	0.299	0.239	0.128	0.132	0.181	0.095	0.228	0.233	0.245	0.222	0.215
MHK‘13	211	6 singles	0.295	0.252	0.185	0.235	0.168	0.134	0.243	0.211	0.288	0.237	0.254
MHK‘13	301	WR	0.288	0.166	0.121	0.175	0.140	0.115	0.213	0.211	0.250	0.200	0.218
MHK‘13	302	PM	0.292	0.230	0.181	0.205	0.132	0.134	0.254	0.243	0.284	0.222	0.260

MHK‘13	303	Fallow	0.299	0.239	0.203	0.254	0.226	0.230	0.307	0.222	0.228	0.209	0.243
MHK‘13	304	TR	0.277	0.188	0.155	0.200	0.136	0.162	0.220	0.205	0.239	0.188	0.207
MHK‘13	305	SS/TR/MRC	0.277	0.168	0.125	0.168	0.164	0.145	0.241	0.213	0.250	0.192	0.233
MHK‘13	306	SS	0.265	0.211	0.140	0.168	0.153	0.155	0.181	0.226	0.254	0.233	0.209
MHK‘13	307	PM/WR/SH	0.299	0.175	0.072	0.194	0.149	0.130	0.248	0.239	0.260	0.233	0.233
MHK‘13	308	SH	0.260	0.136	0.089	0.149	0.134	0.123	0.205	0.243	0.185	0.228	0.245
MHK‘13	309	MRC	0.211	0.205	0.123	0.200	0.151	0.083	0.222	0.203	0.233	0.215	0.248
MHK‘13	310	Mix of 9	0.248	0.203	0.078	0.209	0.162	0.147	0.170	0.220	0.284	0.188	0.230
MHK‘13	311	6 singles	0.260	0.173	0.125	0.192	0.160	0.136	0.267	0.248	0.220	0.239	0.256
MHK‘13	401	WR	0.280	0.155	0.119	0.183	0.138	0.145	0.200	0.151	0.248	0.190	0.226
MHK‘13	402	TR	0.239	0.224	0.147	0.185	0.181	0.162	0.222	0.228	0.222	0.196	0.213
MHK‘13	403	PM/WR/SH	0.269	0.207	0.113	0.218	0.140	0.132	0.205	0.228	0.243	0.213	0.263
MHK‘13	404	6 singles	0.273	0.207	0.143	0.190	0.140	0.132	0.226	0.207	0.239	0.200	0.235
MHK‘13	405	Fallow	0.252	0.177	0.185	0.243	0.205	0.145	0.241	0.226	0.260	0.205	0.164
MHK‘13	406	PM	0.273	0.177	0.136	0.173	0.117	0.113	0.207	0.222	0.245	0.226	0.220
MHK‘13	407	SS	0.292	0.222	0.132	0.175	0.149	0.130	0.239	0.243	0.254	0.226	0.237
MHK‘13	408	Mix of 9	0.250	0.245	0.132	0.194	0.175	0.102	0.243	0.256	0.248	0.224	0.241
MHK‘13	409	MRC	0.260	0.243	0.121	0.190	0.183	0.085	0.192	0.256	0.265	0.198	0.203
MHK‘13	410	SS/TR/MRC	0.303	0.166	0.132	0.220	0.119	0.130	0.282	0.269	0.265	0.228	0.258
MHK‘13	411	SH	0.292	0.194	0.151	0.177	0.164	0.125	0.211	0.265	0.243	0.218	0.245
Site	Plot	Name	8/18/13	8/23/13	9/02/13	9/25/13	10/09/13	11/10/13	12/19/13	2/18/14	3/21/14		
							$cm^3\ cm^{-3}$						
BEL ‘13	501	SS	0.252	0.183	0.115	0.093	0.179	0.286	0.166	0.222	0.250		
BEL ‘13	502	PM/WR/SH	0.256	0.198	0.108	0.106	0.200	0.241	0.143	0.224	0.265		
BEL ‘13	503	Mix of 9	0.248	0.164	0.085	0.057	0.128	0.248	0.158	0.237	0.224		
BEL ‘13	504	WR	0.239	0.207	0.108	0.093	0.200	0.228	0.136	0.158	0.233		

BEL ‘13	505	Fallow	0.254	0.183	0.115	0.110	0.188	0.284	0.181	0.170	0.207
BEL ‘13	506	SS/TR/ MRC	0.305	0.220	0.125	0.098	0.190	0.235	0.121	0.250	0.254
BEL ‘13	507	SH	0.273	0.203	0.130	0.102	0.205	0.200	0.151	0.252	0.211
BEL ‘13	508	6 singles	0.239	0.192	0.091	0.100	0.143	0.230	0.145	0.162	0.205
BEL ‘13	509	TR	0.222	0.175	0.140	0.106	0.173	0.218	0.128	0.228	0.211
BEL ‘13	510	PM	0.269	0.158	0.143	0.113	0.162	0.228	0.136	0.239	0.237
BEL ‘13	511	MRC	0.248	0.181	0.121	0.098	0.190	0.258	0.183	0.252	0.239
BEL ‘13	601	PM/WR /SH	0.243	0.170	0.100	0.102	0.233	0.230	0.170	0.196	0.226
BEL ‘13	602	WR	0.228	0.194	0.125	0.100	0.132	0.226	0.213	0.095	0.235
BEL ‘13	603	SS	0.228	0.192	0.128	0.087	0.188	0.215	0.170	0.190	0.243
BEL ‘13	604	PM	0.256	0.181	0.125	0.070	0.121	0.233	0.175	0.215	0.198
BEL ‘13	605	Fallow	0.239	0.194	0.177	0.136	0.224	0.263	0.164	0.164	0.235
BEL ‘13	606	SS/TR/ MRC	0.271	0.192	0.130	0.076	0.155	0.250	0.125	0.207	0.243
BEL ‘13	607	MRC	0.218	0.188	0.138	0.074	0.119	0.205	0.140	0.181	0.228
BEL ‘13	608	TR	0.237	0.196	0.104	0.048	0.155	0.188	0.166	0.265	0.254
BEL ‘13	609	6 singles	0.237	0.198	0.119	0.072	0.173	0.220	0.134	0.243	0.258
BEL ‘13	610	Mix of 9	0.256	0.209	0.147	0.093	0.170	0.241	0.149	0.235	0.226
BEL ‘13	611	SH	0.228	0.158	0.106	0.059	0.190	0.153	0.166	0.222	0.224
BEL ‘13	701	SH	0.200	0.166	0.119	0.093	0.173	0.224	0.160	0.185	0.235
BEL ‘13	702	SS	0.224	0.168	0.128	0.076	0.143	0.203	0.147	0.198	0.230
BEL ‘13	703	MRC	0.222	0.183	0.076	0.074	0.104	0.241	0.160	0.273	0.181
BEL ‘13	704	PM/WR /SH	0.228	0.194	0.093	0.078	0.166	0.245	0.140	0.239	0.218
BEL ‘13	705	SS/TR/ MRC	0.215	0.250	0.119	0.106	0.198	0.260	0.218	0.196	0.235
BEL ‘13	706	PM	0.260	0.207	0.123	0.119	0.162	0.252	0.166	0.226	0.250
BEL ‘13	707	Mix of 9	0.265	0.181	0.080	0.113	0.153	0.222	0.093	0.260	0.263
BEL ‘13	708	Fallow	0.275	0.168	0.083	0.140	0.175	0.241	0.149	0.194	0.190
BEL ‘13	709	6 singles	0.258	0.194	0.087	0.078	0.175	0.252	0.147	0.237	0.237

BEL ‘13	710	TR	0.230	0.226	0.115	0.083	0.121	0.243	0.160	0.218	0.218
BEL ‘13	711	WR	0.233	0.179	0.095	0.065	0.117	0.209	0.177	0.224	0.226
BEL ‘13	801	Mix of 9	0.213	0.207	0.068	0.078	0.147	0.218	0.138	0.226	0.222
BEL ‘13	802	PM	0.215	0.177	0.121	0.098	0.149	0.175	0.170	0.177	0.200
BEL ‘13	803	PM/WR/SH	0.237	0.196	0.132	0.074	0.153	0.243	0.125	0.211	0.215
BEL ‘13	804	TR	0.245	0.192	0.155	0.098	0.095	0.222	0.136	0.248	0.237
BEL ‘13	805	SS/TR/MRC	0.267	0.207	0.145	0.108	0.134	0.277	0.179	0.271	0.226
BEL ‘13	806	WR	0.310	0.220	0.170	0.119	0.170	0.248	0.188	0.258	0.233
BEL ‘13	807	SH	0.243	0.213	0.130	0.106	0.160	0.256	0.132	0.207	0.190
BEL ‘13	808	Fallow	0.258	0.228	0.121	0.162	0.185	0.233	0.179	0.295	0.256
BEL ‘13	809	MRC	0.254	0.175	0.106	0.095	0.177	0.239	0.140	0.239	0.200
BEL ‘13	810	6 singles	0.241	0.181	0.134	0.095	0.158	0.213	0.168	0.256	0.220
BEL ‘13	811	SS	0.271	0.218	0.098	0.102	0.166	0.271	0.166	0.239	0.237
Site	Plot	Name	7/28/14	8/06/14	8/15/14	8/30/14	9/06/14	9/07/14	9/18/14	10/18/14	1/24/15
							cm^3 cm^{-3}				
MHK ‘14	101	SS	0.123	0.136	0.160	0.110	.	0.168	0.121	0.230	0.095
MHK‘14	102	PM	0.134	0.158	0.188	0.102	.	0.209	0.125	0.224	0.136
MHK‘14	103	Mix of 9	0.132	0.108	0.188	0.119	.	0.230	0.130	0.237	0.166
MHK‘14	104	6 singles	0.153	0.155	0.194	0.134	.	0.233	0.130	0.239	0.177
MHK‘14	105	SH	0.100	0.147	0.207	0.209	.	0.192	0.143	0.209	0.117
MHK‘14	106	WR	0.158	0.179	0.183	0.140	.	0.273	0.149	0.263	0.125
MHK‘14	107	Fallow	0.113	0.145	0.243	0.211	.	0.254	0.183	0.243	0.138
MHK‘14	108	MRC	0.147	0.166	0.192	.	.	.	.	.	.
MHK‘14	109	SS/TR/MRC	0.130	0.143	0.170	0.117	.	0.230	0.121	0.226	0.162
MHK‘14	110	TR	0.164	0.179	0.209	0.179	.	0.337	0.160	0.248	0.153
MHK‘14	111	PM/WR/SH	0.140	0.130	0.147	0.119	.	0.361	0.132	0.254	0.211
MHK‘14	201	TR	0.166	0.179	0.213	0.145	.	0.292	0.149	0.211	0.183

MHK‘14	202	SS/TR/ MRC	0.145	0.164	0.153	0.123	.	0.230	0.158	0.220	0.209
MHK‘14	203	Mix of 9	0.106	0.125	0.138	0.123	.	0.181	0.121	0.230	0.220
MHK‘14	204	6 singles	0.136	0.125	0.164	0.095	.	0.263	0.108	0.222	0.123
MHK‘14	205	PM/WR /SH	0.128	0.134	0.175	0.130	.	0.290	0.108	0.258	0.203
MHK‘14	206	WR	0.110	0.177	0.183	0.153	.	0.329	0.119	0.205	0.203
MHK‘14	207	MRC	0.158	0.168	0.194	.	.	.	.	.	.
MHK‘14	208	SH	0.147	0.181	0.203	0.145	.	0.295	0.128	0.209	0.175
MHK‘14	209	Fallow	0.138	0.121	0.209	0.218	.	0.226	0.192	0.226	0.211
MHK‘14	210	SS	0.166	0.173	0.185	0.134	.	0.252	0.132	0.248	0.211
MHK‘14	211	PM	0.134	0.177	0.198	0.136	.	0.235	0.194	0.245	0.213
MHK‘14	301	TR	0.166	0.130	0.168	0.130	0.147	.	0.140	0.207	0.151
MHK‘14	302	6 singles	0.113	0.110	0.164	0.100	0.080	.	0.132	0.220	0.200
MHK‘14	303	SS	0.123	0.119	0.177	0.125	0.121	.	0.140	0.269	0.192
MHK‘14	304	SH	0.170	0.143	0.188	0.130	0.125	.	0.153	0.222	0.153
MHK‘14	305	PM/WR /SH	0.145	0.188	0.200	0.130	0.170	.	0.166	0.260	0.205
MHK‘14	306	SS/TR/ MRC	0.175	0.185	0.220	0.164	0.149	.	0.151	0.215	0.168
MHK‘14	307	Fallow	0.166	0.200	0.211	0.235	0.228	.	0.226	0.239	0.153
MHK‘14	308	WR	0.132	0.175	0.194	0.119	0.125	.	0.151	0.250	0.151
MHK‘14	309	PM	0.138	0.130	0.162	0.128	0.145	.	0.115	0.258	0.190
MHK‘14	310	MRC	0.203	0.213	0.243	.	.	.	.	.	.
MHK‘14	311	Mix of 9	0.134	0.136	0.166	0.160	0.140	.	0.143	0.267	0.239
MHK‘14	401	6 singles	0.136	0.132	0.196	0.106	0.147	.	0.110	0.222	0.205
MHK‘14	402	PM/WR /SH	0.149	0.123	0.213	0.098	0.205	.	0.198	0.224	0.123
MHK‘14	403	TR	0.160	0.153	0.170	0.138	0.177	.	0.123	0.218	0.200
MHK‘14	404	Fallow	0.147	0.185	0.215	0.194	0.205	.	0.213	0.241	0.203
MHK‘14	405	SS	0.108	0.123	0.151	0.119	0.110	.	0.083	0.185	0.160
MHK‘14	406	WR	0.155	0.138	0.188	0.145	0.168	.	0.132	0.218	0.209

MHK'14	407	SS/TR/ MRC	0.125	0.149	0.205	0.170	0.209	.	0.177	0.256	0.181
MHK'14	408	PM	0.134	0.132	0.164	0.147	0.164	.	0.140	0.271	0.143
MHK'14	409	Mix of 9	0.192	0.121	0.203	0.158	0.138	.	0.158	0.237	0.233
MHK'14	410	MRC	0.170	0.160	0.196	.	.	.	.	.	.
MHK'14	411	SH	0.177	0.211	0.200	0.100	0.125	.	0.125	0.277	0.243

Site	Plot	Name	7/22/14	8/01/14	8/12/14	8/24/14	9/06/14	9/21/14	10/23/14	1/28/15
			$cm^3\ cm^{-3}$							
BEL '14	501	6 singles	0.363	0.286	0.447	0.329	0.402	0.333	0.410	0.288
BEL '14	502	Fallow	0.292	0.389	0.445	0.391	0.601	0.370	0.438	0.237
BEL '14	503	PM	0.258	0.286	0.367	0.297	0.331	0.241	0.325	0.243
BEL '14	504	Mix of 9	0.230	0.119	0.288	0.198	0.211	0.207	0.310	0.235
BEL '14	505	TR	0.222	0.158	0.271	0.168	0.233	0.160	0.256	0.205
BEL '14	506	MRC	0.307	0.250	0.269	0.245	0.277	0.254	0.273	0.200
BEL '14	507	SH	0.295	0.314	0.342	0.310	0.215	0.222	0.307	0.173
BEL '14	508	SS	0.209	0.252	0.370	0.228	0.220	0.282	0.333	0.263
BEL '14	509	WR	0.292	0.220	0.376	0.258	0.200	0.235	0.329	0.243
BEL '14	510	SS/TR/ MRC	0.312	0.297	0.350	0.318	0.155	0.196	0.297	0.230
BEL '14	511	PM/WR /SH	0.290	0.198	0.318	0.256	0.181	0.224	0.325	0.233
BEL '14	601	SH	0.209	0.166	0.385	0.224	0.425	0.181	0.325	0.196
BEL '14	602	Fallow	0.220	0.258	0.357	0.275	0.556	0.295	0.292	0.207
BEL '14	603	SS/TR/ MRC	0.250	0.260	0.346	0.198	0.297	0.198	0.312	0.213
BEL '14	604	PM/WR /SH	0.209	0.134	0.282	0.230	0.273	0.168	0.303	0.151
BEL '14	605	TR	0.205	0.138	0.254	0.211	0.218	0.130	0.295	0.188
BEL '14	606	PM	0.226	0.089	0.254	0.166	0.185	0.173	0.252	0.203
BEL '14	607	MRC	0.162	0.160	0.243	0.145	0.295	0.158	0.203	0.147
BEL '14	608	WR	0.175	0.130	0.248	0.151	0.230	0.158	0.239	0.173

BEL '14	609	6 singles	0.177	0.147	0.241	0.113	0.256	0.175	0.224	0.205
BEL '14	610	Mix of 9	0.134	0.100	0.224	0.147	0.222	0.132	0.230	0.200
BEL '14	611	SS	0.145	0.143	0.252	0.162	0.233	0.151	0.237	0.209
BEL '14	701	SH	0.181	0.173	0.235	0.160	0.233	0.149	0.222	0.177
BEL '14	702	6 singles	0.192	0.119	0.220	0.104	0.468	0.108	0.211	0.194
BEL '14	703	WR	0.211	0.188	0.254	0.102	0.241	0.136	0.252	0.158
BEL '14	704	PM/WR /SH	0.149	0.098	0.241	0.132	0.228	0.164	0.258	0.200
BEL '14	705	SS	0.196	0.158	0.248	0.095	0.207	0.164	0.256	0.205
BEL '14	706	TR	0.134	0.115	0.218	0.132	0.327	0.098	0.237	0.145
BEL '14	707	MRC	0.162	0.183	0.226	0.181	0.237	0.155	0.166	0.158
BEL '14	708	Mix of 9	0.132	0.098	0.213	0.136	0.185	0.168	0.245	.
BEL '14	709	SS/TR/ MRC	0.160	0.190	0.344	0.102	0.203	0.153	0.250	.
BEL '14	710	PM	0.138	0.102	0.256	0.173	0.472	0.198	0.241	0.170
BEL '14	711	Fallow	0.162	0.170	0.254	0.271	0.220	0.243	0.245	0.170
BEL '14	801	6 singles	0.211	0.140	0.248	0.104	0.254	0.147	0.258	0.179
BEL '14	802	Fallow	0.173	0.196	0.340	0.245	0.295	0.269	0.350	0.153
BEL '14	803	SH	0.188	0.209	0.269	0.098	0.224	0.136	0.235	0.181
BEL '14	804	SS	0.192	0.123	0.250	0.087	0.205	0.136	0.224	0.185
BEL '14	805	PM/WR /SH	0.192	0.119	0.243	0.117	0.233	0.145	0.235	0.153
BEL '14	806	TR	0.218	0.181	0.237	0.128	0.230	0.138	0.230	0.183
BEL '14	807	WR	0.192	0.106	0.248	0.102	0.211	0.132	0.218	0.188
BEL '14	808	PM	0.239	0.151	0.263	0.117	0.192	0.175	0.256	0.181
BEL '14	809	Mix of 9	0.188	0.136	0.248	0.121	0.442	0.130	0.241	0.168
BEL '14	810	MRC	0.220	0.192	0.273	0.200	0.359	0.166	0.200	0.149
BEL '14	811	SS/TR/ MRC	0.226	0.132	0.260	0.164	0.226	0.143	0.237	0.151

Table A.3 Cover crop biomass, water use, and C:N. Data used to generate Tables 2.1-2.4.

Plot	Crop Type	Name	Jul-Sep WU	Jul-Nov WU	Jul-Jan WU	Sep-Nov WU	Nov-Jan WU	Dry Matter	C:N
			inches					kg ha^{-1}	X:1
134	SNL	sorghum-sudangrass	6.85	9.59	11.20	2.75	1.61	6194	35.57
138	WL	crimson clover	6.00	9.73	11.50	3.73	1.77	3636	18.52
143	CF	fallow	3.87	6.46	8.71	2.59	2.25	.	.
149	DSB	double crop soy	6.97	9.72	11.72	2.75	2.00	2507	.
153	SL	forage soybeans	6.93	9.30	10.96	2.36	1.66	4080	16.67
158	WNL	tillage radish	6.28	9.47	10.85	3.18	1.38	2052	25.84
264	WL	crimson clover	5.54	10.34	11.80	4.80	1.46	3353	17.59
267	CF	fallow	3.71	6.95	9.24	3.24	2.29	.	.
271	SNL	sorghum-sudangrass	6.21	8.88	10.30	2.67	1.42	7990	38.28
277	WNL	tillage radish	7.07	10.32	11.88	3.25	1.56	3287	26.05
284	DSB	double crop soy	5.92	9.24	10.97	3.32	1.73	3913	.
290	SL	forage soybeans	6.98	10.52	12.01	3.54	1.49	3274	15.09
334	CF	fallow	3.65	6.81	8.69	3.16	1.89	.	.
338	WL	crimson clover	5.92	9.86	11.14	3.95	1.27	3447	18.19
341	SNL	sorghum-sudangrass	5.97	8.25	9.98	2.28	1.73	6089	41.48
356	SL	forage soybeans	6.91	9.53	10.48	2.62	0.95	4134	15.92
352	WNL	tillage radish	7.22	10.50	11.49	3.28	0.99	2436	21.21
348	DSB	double crop soy	.	.	.	.	.	3232	.
461	WL	crimson clover	5.30	9.51	11.24	4.20	1.73	2950	18.24
466	DSB	double crop soy	5.94	8.82	10.22	2.87	1.41	3513	.
476	SNL	sorghum-sudangrass	6.64	9.01	10.66	2.37	1.64	6443	40.51
481	SL	forage soybeans	6.50	9.62	11.10	3.12	1.48	3294	16.20
486	WNL	tillage radish	6.87	10.10	11.37	3.23	1.27	2952	25.22
474	CF	fallow	5.04	7.85	10.02	2.81	2.17	.	.

Table A.4 Surface soil volumetric water content values. Data used to generate Figure 2.3.

Plot	Crop type	Name	21 July	31 July	11 Aug	23 Aug	2 Sept	16 Sept	19 Oct	10 Nov	26 Jan
			$cm^3\ cm^{-3}$								
134	SNL	sorghum-sudangrass	0.207	0.179	0.258	0.110	0.233	0.134	0.185	0.160	0.196
138	WL	crimson clover	0.241	0.280	0.322	0.215	0.290	0.134	0.196	0.074	0.188
143	CF	fallow	0.280	0.250	0.337	0.235	0.327	0.248	0.198	0.185	0.207
149	DSB	double crop soy	0.205	0.205	0.256	0.138	0.263	0.121	0.224	0.121	0.140
153	SL	forage soybeans	0.188	0.213	0.307	0.115	0.248	0.130	0.198	0.130	0.175
158	WNL	tillage radish	0.209	0.196	0.260	0.117	0.250	0.162	0.239	0.119	0.213
264	WL	crimson clover	0.284	0.248	0.378	0.250	0.256	0.155	0.235	0.123	0.207
267	CF	fallow	0.280	0.256	0.344	0.288	0.327	0.269	0.230	0.175	0.203
271	SNL	sorghum-sudangrass	0.192	0.192	0.303	0.170	0.252	0.205	0.269	0.239	0.220
277	WNL	tillage radish	0.265	0.267	0.230	0.252	0.307	0.254	0.211	0.158	0.185
284	DSB	double crop soy	0.196	0.213	0.355	0.149	0.329	0.177	0.218	0.151	0.175
290	SL	forage soybeans	0.209	0.355	0.297	0.203	0.301	0.215	0.215	0.160	0.183
334	CF	fallow	0.179	0.211	0.329	0.250	0.292	0.237	0.237	0.162	0.190
338	WL	crimson clover	0.252	0.263	0.320	0.151	0.269	0.117	0.175	0.055	0.207
341	SNL	sorghum-sudangrass	0.258	0.179	0.297	0.115	0.173	0.074	0.230	0.162	0.198
356	SL	forage soybeans	0.284	0.258	0.322	0.185	0.233	0.130	0.211	0.166	0.194
352	WNL	tillage radish	0.188	0.237	0.273	0.168	0.312	0.205	0.258	0.125	0.185
348	DSB	double crop soy	0.241	0.213	0.280	0.145	.	.	.	.	.
461	WL	crimson clover	0.316	0.314	0.442	0.348	0.342	0.228	0.254	0.128	0.271
466	DSB	double crop soy	0.275	0.209	0.348	0.113	0.250	0.177	0.282	0.198	0.297
476	SNL	sorghum-sudangrass	0.415	0.286	0.258	0.194	0.209	0.299	0.280	0.188	0.320
481	SL	forage soybeans	0.333	0.241	0.402	0.239	0.329	0.160	0.254	0.228	0.267
486	WNL	tillage radish	0.224	0.237	0.400	0.307	0.297	0.243	0.284	0.196	0.297
474	CF	fallow	0.320	0.267	0.372	0.177	0.359	0.282	0.245	0.203	0.235

Appendix B - SAS Code

Table B.1 SAS code for Chapter 2 water use, dry matter, C:N.

```
      DATA RCB; SET RCB;

        BIOMkgha = BIOMlba / 0.893;
        Jul_Sep_dW_mm = Jul_Sep_dW_in * 25.4;
        Jul_Nov_dW_mm = Jul_Nov_dW_in * 25.4;
        Jul_Jan_dW_mm = Jul_Jan_dW_in * 25.4;
        Sep_Nov_dW_mm = Sep_Nov_dW_in * 25.4;
        Nov_Jan_dW_mm = Nov_Jan_dW_in * 25.4;
        Summer_WUE_kgmm = BIOMkgha / Jul_Sep_dW_mm;
        Summer_WUE_lbin = BIOMlba / Jul_Sep_dW_in;
        Fall_WUE_kgmm = BIOMkgha / Jul_Nov_dW_mm;
        Fall_WUE_lbin = BIOMlba / Jul_Nov_dW_in;
        Winter_WUE_kgmm = BIOMkgha / Jul_Jan_dW_mm;
        Winter_WUE_lbin = BIOMlba / Jul_Jan_dW_in;
        *mmPkg = CCWU_mm / BIOMkgha;
        *inPlb = CCWU_in / BIOMlba;
        RUN;
      PROC SORT; BY YEAR;
      RUN;
      PROC PRINT DATA=RCB;
      RUN;
      %macro mixanova/parmbuff;
        %PUT ***Syspbuff contains: &syspbuff***;
         %let num=1;
         %let respvar=%scan(&syspbuff,&num);
         %do %while(&respvar ne);
      PROC GLIMMIX DATA=RCB; TITLE2 'GL MIXED MODEL RCB ANALYSIS
WITHOUT SPATIAL COVARIATE';
       CLASS BLOC Name; *BY YEAR LOC;
       MODEL &respvar = Name/DDFM=SATTERTH;
       RANDOM BLOC;
       LSMEANS Name/LINES;
       LSMEANS Name/PDIFF;
      %let num=%eval(&num+1);
            %let respvar=%scan(&syspbuff,&num);
         %end;
      %mend mixanova;
      %mixanova(BIOMkgha Jul_Sep_dW_mm Jul_Nov_dW_mm
Jul_Jan_dW_mm Sep_Nov_dW_mm Nov_Jan_dW_mm Summer_WUE_kgmm
Fall_WUE_kgmm Winter_WUE_kgmm BIOMlba Jul_Sep_dW_in
Jul_Nov_dW_in Jul_Jan_dW_in Sep_Nov_dW_in Nov_Jan_dW_in
Summer_WUE_lbin Fall_WUI_lbin Winter_WUE_lb_in C_N);RUN;
```

Table B.2 SAS code for Chapter 2 surface water contents.

```
      DATA RCB; SET RCB;
      Run;

      PROC SORT; BY YEAR;
      RUN;

      PROC PRINT DATA=RCB;
      RUN;

      %macro mixanova/parmbuff;

        %PUT ***Syspbuff contains: &syspbuff***;
         %let num=1;
         %let respvar=%scan(&syspbuff,&num);
         %do %while(&respvar ne);

      PROC GLIMMIX DATA=RCB; TITLE2 'GL MIXED MODEL RCB ANALYSIS
WITHOUT SPATIAL COVARIATE';
       CLASS BLOC Name; *BY YEAR LOC;
       MODEL &respvar = Name/DDFM=SATTERTH;
       RANDOM BLOC;
       LSMEANS Name/LINES;
       LSMEANS Name/PDIFF;

      %let num=%eval(&num+1);
            %let respvar=%scan(&syspbuff,&num);
         %end;
      %mend mixanova;


      %mixanova(TDR_7_21_14,TDR_7_31_14,TDR_8_11_14,TDR_8_23_14,
TDR_9_2_14,TDR_9_16_14,TDR_10_19_14,TDR_11_10_14,TDR_1_26_15);
      RUN;
      QUIT;
```

Table B.3 SAS code for Chapter 1

```
DATA RCB; SET RCB;
Run;

PROC SORT; BY YEAR LOC;
RUN;

PROC PRINT DATA=RCB;
RUN;

%macro mixanova/parmbuff;

  %PUT ***Syspbuff contains: &syspbuff***;
   %let num=1;
   %let respvar=%scan(&syspbuff,&num);
   %do %while(&respvar ne);

PROC GLIMMIX DATA=RCB; TITLE2 'GL MIXED MODEL RCB ANALYSIS
WITHOUT SPATIAL COVARIATE';
 CLASS BLOC Name; By YEAR LOC;
 MODEL &respvar = Name/DDFM=SATTERTH;
 RANDOM BLOC;
 LSMEANS Name/LINES;

%let num=%eval(&num+1);
      %let respvar=%scan(&syspbuff,&num);
   %end;
%mend mixanova;

%mixanova(Date1,Date2,Date3,Date4,Date5,Date6,Date7,Date8,
Date9,Date10,Date11,Date12);
RUN;
QUIT;
```

Appendix C - Additional Tables

Table C.1 Surface soil water content at Manhattan, KS 2013-14†.

Treatment	17 Aug		22 Aug		1 Sept		13 Sept		22 Sept		27 Sept	
	$cm^3\ cm^{-3}$											
Fallow	0.278	ab	0.213	a	0.188	a	0.248	a	0.212	a	0.202	a
Sorghum-sudangrass	0.285	ab	0.210	a	0.134	bcd	0.178	b	0.145	b	0.121	bc
Pearl millet	0.296	a	0.216	a	0.148	bc	0.192	b	0.166	b	0.106	bc
Tillage radish	0.267	ab	0.203	ab	0.148	bc	0.188	b	0.155	b	0.132	bc
Winfred rape	0.272	ab	0.182	ab	0.126	bcd	0.205	b	0.145	b	0.099	bc
Medium red clover	0.253	b	0.205	ab	0.125	bcd	0.198	b	0.168	b	0.080	c
Sunn hemp	0.274	ab	0.168	b	0.112	d	0.180	b	0.162	b	0.112	bc
Mix of SS/TR/MRC	0.298	a	0.203	ab	0.133	bcd	0.179	b	0.152	b	0.103	bc
Mix of PM/WR/SH	0.274	ab	0.200	ab	0.117	cd	0.205	b	0.179	ab	0.134	b
Mix of 6	0.271	ab	0.207	ab	0.153	b	0.204	b	0.160	b	0.123	bc
Mix of 9	0.274	ab	0.221	a	0.123	bcd	0.206	b	0.174	ab	0.139	b
	6 Oct		10 Oct		20 Nov		19 Jan		18 Mar		15 Apr	
Fallow	0.257	ab	0.247	a	0.218	ab	0.269	a	0.199	cd	0.205	b
Sorghum-sudangrass	0.233	b	0.222	a	0.231	ab	0.243	ab	0.230	ab	0.233	ab
Pearl millet	0.261	ab	0.239	a	0.234	a	0.271	a	0.235	a	0.243	a
Tillage radish	0.267	ab	0.227	a	0.219	ab	0.241	ab	0.189	d	0.219	ab
Winfred rape	0.240	ab	0.222	a	0.200	b	0.251	a	0.208	bcd	0.233	ab
Medium red clover	0.238	ab	0.213	a	0.224	ab	0.249	ab	0.202	cd	0.217	ab
Sunn hemp	0.236	ab	0.211	a	0.225	ab	0.221	b	0.198	cd	0.219	ab
Mix of SS/TR/MRC	0.238	ab	0.248	a	0.230	ab	0.256	a	0.216	abc	0.245	a
Mix of PM/WR/SH	0.269	a	0.231	a	0.219	ab	0.255	a	0.218	abc	0.244	a
Mix of 6	0.257	ab	0.237	a	0.221	ab	0.265	a	0.230	ab	0.243	a
Mix of 9	0.262	ab	0.226	a	0.227	ab	0.267	a	0.211	abcd	0.247	a

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table C.2 Surface soil water content at Manhattan, KS 2014-15†.

Treatment	28 July		6 Aug		15 Aug		30 Aug		18 Sept		18 Oct		24 Jan	
	$cm^3\ cm^{-3}$													
Fallow	0.140	abc	0.162	abc	0.220	a	0.214	a	0.203	a	0.237	a	0.176	ab
Sorghum-sudangrass	0.130	c	0.137	bcd	0.168	d	0.121	bc	0.118	b	0.233	a	0.164	b
Pearl millet	0.134	bc	0.148	abcd	0.178	bcd	0.127	bc	0.143	b	0.250	a	0.170	ab
Tillage radish	0.164	ab	0.160	abc	0.190	abcd	0.147	b	0.142	b	0.221	a	0.172	ab
Winfred rape	0.138	abc	0.167	ab	0.187	bcd	0.139	bc	0.137	b	0.234	a	0.172	ab
Medium red clover	0.167	a	0.176	a	0.206	ab	-	-	-	-	-	-	-	-
Sunn hemp	0.148	abc	0.170	ab	0.199	abc	0.145	b	0.137	b	0.229	a	0.172	ab
Mix of SS/TR/MRC	0.143	abc	0.160	abc	0.187	bcd	0.143	b	0.151	b	0.229	a	0.180	ab
Mix of PM/WR/SH	0.140	abc	0.143	abcd	0.183	bcd	0.118	bc	0.151	b	0.249	a	0.185	ab
Mix of 6	0.134	bc	0.130	cd	0.179	bcd	0.108	c	0.119	b	0.226	a	0.176	ab
Mix of 9	0.140	abc	0.122	d	0.173	cd	0.139	bc	0.137	b	0.243	a	0.214	a

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table C.3 Surface soil water content at Belleville, KS 2013-14†.

Treatment	18 Aug		23 Aug		2 Sept		25 Sept		9 Oct		10 Nov	
	$cm^3\ cm^{-3}$											
Fallow	0.257	a	0.193	ab	0.123	ab	0.137	a	0.193	a	0.255	a
Sorghum-sudangrass	0.244	a	0.190	ab	0.116	ab	0.089	b	0.168	abcd	0.244	ab
Pearl millet	0.250	a	0.180	b	0.127	a	0.099	b	0.148	cd	0.222	ab
Tillage radish	0.234	a	0.197	ab	0.128	a	0.083	b	0.135	d	0.217	b
Winfred rape	0.253	a	0.200	ab	0.124	ab	0.093	b	0.154	abcd	0.228	ab
Medium red clover	0.235	a	0.181	b	0.110	ab	0.084	b	0.147	cd	0.236	ab
Sunn hemp	0.236	a	0.185	b	0.120	ab	0.089	b	0.181	abc	0.208	b
Mix of SS/TR/MRC	0.265	a	0.217	a	0.129	a	0.096	b	0.169	abcd	0.256	a
Mix of PM/WR/SH	0.241	a	0.189	ab	0.107	ab	0.089	b	0.188	ab	0.240	ab
Mix of 6	0.244	a	0.191	ab	0.107	ab	0.085	b	0.161	abcd	0.229	ab
Mix of 9	0.245	a	0.190	ab	0.094	b	0.084	b	0.149	bcd	0.232	ab

	19 Dec		18 Feb		21 Mar	
Fallow	0.168	ab	0.206	ab	0.222	a
Sorghum-sudangrass	0.162	ab	0.212	ab	0.240	a
Pearl millet	0.161	ab	0.214	ab	0.221	a
Tillage radish	0.147	ab	0.240	a	0.230	a
Winfred rape	0.178	a	0.183	b	0.231	a
Medium red clover	0.155	ab	0.236	ab	0.212	a
Sunn hemp	0.152	ab	0.216	ab	0.215	a
Mix of SS/TR/MRC	0.160	ab	0.231	ab	0.240	a
Mix of PM/WR/SH	0.144	ab	0.217	ab	0.231	a
Mix of 6	0.148	ab	0.224	ab	0.230	a
Mix of 9	0.134	b	0.240	a	0.234	a

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table C.4 Surface soil water content at Belleville, KS 2014-15†.

Treatment	22 July		1 Aug		12 Aug		24 Aug		6 Sept		21 Sept		23 Oct		28 Jan	
	$cm^3\ cm^{-3}$															
Fallow	0.212	abc	0.254	a	0.350	a	0.296	a	0.419	a	0.295	a	0.332	a	0.192	abc
Sorghum-sudangrass	0.185	bc	0.168	bcdef	0.280	bcd	0.142	b	0.216	b	0.183	b	0.263	b	0.245	a
Tillage radish	0.194	abc	0.147	def	0.245	d	0.159	b	0.252	b	0.131	c	0.255	bc	0.180	bc
Medium red clover	0.213	abc	0.196	abcd	0.253	cd	0.193	b	0.292	ab	0.183	b	0.210	c	0.163	c
Pearl millet	0.215	abc	0.157	def	0.285	bcd	0.188	b	0.296	ab	0.196	b	0.269	b	0.199	ab
Winfred rape	0.217	ab	0.160	cdef	0.282	bcd	0.153	b	0.221	b	0.165	bc	0.260	bc	0.190	abc
Sunn hemp	0.218	ab	0.215	abc	0.308	abc	0.197	b	0.275	b	0.172	b	0.272	b	0.181	bc
Mix of SS/TR/MRC	0.234	a	0.220	ab	0.326	ab	0.195	b	0.220	b	0.172	b	0.274	b	0.193	abc
Mix of PM/WR/SH	0.210	abc	0.137	ef	0.271	bcd	0.183	b	0.229	b	0.175	b	0.281	b	0.184	bc
Mix of 6	0.236	a	0.173	bcde	0.289	bcd	0.162	b	0.346	ab	0.190	b	0.276	b	0.216	a
Mix of 9	0.171	c	0.112	f	0.243	d	0.150	b	0.265	b	0.159	bc	0.257	bc	0.196	ab

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table C.5 Surface soil water content for Chapter 2†.

Treatment	21 July		31 July		11 Aug		23 Aug		2 Sept		16 Sept		19 Oct		10 Nov		26 Jan	
	$cm^3\ cm^{-3}$																	
Fallow	0.265	a	0.246	ab	0.346	ab	0.237	a	0.327	a	0.259	a	0.228	ab	0.181	ab	0.208	ab
Sorghum-sudangrass	0.268	a	0.209	b	0.279	c	0.147	b	0.216	b	0.178	bc	0.241	ab	0.187	a	0.234	a
Forage soybean	0.254	a	0.267	a	0.333	abc	0.185	ab	0.278	a	0.158	c	0.220	ab	0.171	ab	0.205	ab
Crimson clover	0.274	a	0.276	a	0.367	a	0.241	a	0.290	a	0.158	c	0.215	b	0.094	c	0.218	ab
Double-crop soybean	0.229	a	0.210	b	0.310	abc	0.135	b	0.276	a	0.146	c	0.239	ab	0.150	b	0.197	b
Tillage radish	0.221	a	0.234	ab	0.291	bc	0.211	ab	0.216	b	0.216	ab	0.248	a	0.149	b	0.220	ab

†Values in a column followed by the same letter are not significantly different, α=0.05.

Appendix D - Corn after Cover Crops

Materials and Methods

Corn (*Zea mays* L.) hybrid DKC-63-33RIB was planted on 17 April 2014 following the 2013-14 cover crops in Manhattan using a four-row planter, 0.76-m row spacing, and 32,000 seeds acre^{-1}. Nitrogen in the form of 28% UAN was applied below the surface residue with a coulter applicator at 157 kg ha^{-1} when the corn was in the four-leaf vegetative growth stage. Neutron probe access tubes were installed in plots that had previously been in fallow and tillage radish treatments, and readings were taken down to 2.59 m on six dates: 3 May, 26 May, 11 June, 30 June, 21 July, and 11 August (Table D.3). Surface soil moisture was also recorded on those dates using a Field Scout TDR 300 in the tillage radish and fallow plots (Table D.2). Corn was harvested with a plot combine on 5 September 2014. Corn yield and number of fired leaves following all cover crop treatments were recorded (Table D.1).

Table D.1 Corn yields and number of fired leaves following 2013-14 Manhattan cover crops†.

Cover crop treatment	Yield		Fired leaves	
	kg ha^{-1}		number	
Fallow	860	ab	3.04	e
Sorghum-sudangrass	742	cd	4.93	a
Tillage radish	841	abc	4.38	abcd
Medium red clover	841	abc	4.38	abcd
Pearl millet	751	bcd	4.81	ab
Winfred rape	865	ab	4.89	ab
Sunn hemp	898	a	3.83	d
Mix of SS/TR/MRC	749	bcd	3.98	cd
Mix of PM/WR/SH	808	abcd	4.45	abc
Mix of 6	717	d	3.99	cd
Mix of 9	775	bcd	4.21	bcd

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table D.2 Surface water content in corn following tillage radish and fallow cover crop treatments of 2013-14 at five dates†.

Previous cover crop treatment	3 May		26 May		11 June		30 June		11 August	
	$cm^3\ cm^{-3}$									
Tillage Radish	0.2582	a	0.3358	a	0.2866	a	0.1736	a	0.2555	a
Fallow	0.2577	a	0.3642	a	0.2946	a	0.1752	a	0.2325	a

†Values in a column followed by the same letter are not significantly different, α=0.05.

Table D.3 Volumetric water content in 2014 corn following tillage radish and fallow cover crop treatments of 2013-14.

Treatment	Depth	3 May	26 May	11 June	30 June	21 July	11 Aug
	ft.			$cm^3\ cm^{-3}$			
Tillage Radish	8.5	0.255	0.263	0.280	0.285	0.287	0.283
Tillage Radish	7.5	0.246	0.247	0.276	0.285	0.283	0.284
Tillage Radish	6.5	0.245	0.252	0.288	0.300	0.296	0.292
Tillage Radish	5.5	0.247	0.244	0.310	0.313	0.309	0.302
Tillage Radish	4.5	0.243	0.240	0.300	0.305	0.302	0.293
Tillage Radish	3.5	0.284	0.308	0.315	0.311	0.278	0.282
Tillage Radish	2.5	0.327	0.328	0.331	0.324	0.268	0.275
Tillage Radish	1.5	0.316	0.322	0.333	0.307	0.226	0.230
Tillage Radish	0.5	0.290	0.299	0.305	0.215	0.140	0.188
Fallow	8.5	0.258	0.251	0.254	0.280	0.276	0.280
Fallow	7.5	0.245	0.247	0.248	0.280	0.277	0.276
Fallow	6.5	0.253	0.255	0.280	0.293	0.297	0.289
Fallow	5.5	0.247	0.252	0.314	0.310	0.305	0.303
Fallow	4.5	0.281	0.284	0.313	0.311	0.300	0.293
Fallow	3.5	0.325	0.316	0.322	0.317	0.308	0.279
Fallow	2.5	0.327	0.323	0.333	0.328	0.288	0.267
Fallow	1.5	0.321	0.325	0.329	0.298	0.241	0.232
Fallow	0.5	0.298	0.300	0.305	0.223	0.136	0.194
Tillage Radish	8.5	0.255	0.255	0.253	0.255	0.251	0.249
Tillage Radish	7.5	0.252	0.250	0.254	0.249	0.251	0.253
Tillage Radish	6.5	0.254	0.245	0.254	0.249	0.248	0.255
Tillage Radish	5.5	0.235	0.239	0.240	0.239	0.244	0.250
Tillage Radish	4.5	0.230	0.233	0.250	0.275	0.269	0.262
Tillage Radish	3.5	0.265	0.266	0.309	0.311	0.270	0.254
Tillage Radish	2.5	0.312	0.318	0.317	0.313	0.249	0.239
Tillage Radish	1.5	0.326	0.328	0.343	0.303	0.236	0.232
Tillage Radish	0.5	0.296	0.298	0.310	0.221	0.169	0.208
Fallow	8.5	0.269	0.271	0.275	0.276	0.283	0.290
Fallow	7.5	0.267	0.264	0.260	0.281	0.279	0.274
Fallow	6.5	0.259	0.266	0.276	0.283	0.281	0.275
Fallow	5.5	0.276	0.277	0.298	0.291	0.294	0.286
Fallow	4.5	0.306	0.303	0.316	0.310	0.308	0.300
Fallow	3.5	0.308	0.305	0.314	0.309	0.285	0.274
Fallow	2.5	0.318	0.319	0.320	0.320	0.258	0.251
Fallow	1.5	0.332	0.341	0.337	0.304	0.243	0.250
Fallow	0.5	0.297	0.302	0.305	0.206	0.145	0.228
Fallow	8.5	0.266	0.271	0.278	0.281	0.290	0.282
Fallow	7.5	0.275	0.272	0.283	0.284	0.287	0.286
Fallow	6.5	0.295	0.293	0.296	0.298	0.300	0.297
Fallow	5.5	0.302	0.300	0.302	0.307	0.310	0.300
Fallow	4.5	0.310	0.310	0.318	0.307	0.309	0.305
Fallow	3.5	0.317	0.318	0.321	0.324	0.299	0.278

Fallow	2.5	0.332	0.334	0.334	0.332	0.283	0.274
Fallow	1.5	0.334	0.341	0.337	0.316	0.263	0.262
Fallow	0.5	0.302	0.307	0.307	0.235	0.157	0.199
Tillage Radish	8.5	0.257	0.260	0.256	0.261	0.257	0.262
Tillage Radish	7.5	0.239	0.241	0.240	0.242	0.248	0.248
Tillage Radish	6.5	0.249	0.250	0.251	0.259	0.266	0.260
Tillage Radish	5.5	0.263	0.259	0.267	0.275	0.283	0.274
Tillage Radish	4.5	0.250	0.253	0.283	0.297	0.298	0.289
Tillage Radish	3.5	0.271	0.272	0.309	0.310	0.288	0.261
Tillage Radish	2.5	0.326	0.327	0.330	0.326	0.264	0.249
Tillage Radish	1.5	0.338	0.339	0.348	0.326	0.259	0.256
Tillage Radish	0.5	0.295	0.300	0.304	0.208	0.159	0.199
Tillage Radish	8.5	0.255	0.254	0.255	0.266	0.264	0.262
Tillage Radish	7.5	0.254	0.259	0.267	0.268	0.271	0.268
Tillage Radish	6.5	0.268	0.270	0.292	0.288	0.285	0.281
Tillage Radish	5.5	0.290	0.286	0.311	0.300	0.297	0.291
Tillage Radish	4.5	0.312	0.307	0.313	0.312	0.304	0.299
Tillage Radish	3.5	0.316	0.315	0.319	0.325	0.293	0.277
Tillage Radish	2.5	0.320	0.322	0.316	0.317	0.278	0.264
Tillage Radish	1.5	0.320	0.321	0.323	0.300	0.247	0.245
Tillage Radish	0.5	0.300	0.311	0.310	0.237	0.174	0.226
Fallow	8.5	0.273	0.284	0.303	0.291	0.295	0.289
Fallow	7.5	0.272	0.285	0.288	0.282	0.288	0.279
Fallow	6.5	0.289	0.292	0.305	0.305	0.295	0.293
Fallow	5.5	0.306	0.306	0.310	0.307	0.305	0.303
Fallow	4.5	0.314	0.314	0.318	0.315	0.309	0.308
Fallow	3.5	0.311	0.316	0.312	0.317	0.303	0.280
Fallow	2.5	0.318	0.322	0.326	0.323	0.270	0.270
Fallow	1.5	0.318	0.314	0.323	0.281	0.221	0.234
Fallow	0.5	0.294	0.302	0.302	0.217	0.153	0.206