THESIS

CROP RESIDUE: A HERO'S JOURNEY FROM BIOMASS TO SOIL CARBON IN EASTERN COLORADO DRYLAND CROP ROTATION SYSTEMS

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ABSTRACT

CROP RESIDUE: A HERO'S JOURNEY FROM BIOMASS TO SOIL CARBON IN EASTERN COLORADO DRYLAND CROP ROTATION SYSTEMS

Crop residues play a vital role in reducing the potential for wind erosion of agricultural soils in arid and semi-arid regions. The residues act via three modes: reducing wind speed, acting as a physical impediment to wind reaching the soil surface, and as an organic matter input to spur aggregation and aggregate stability. The interactions of crop residues, crop rotation systems, and wind erosion factors were studied at three long-term agricultural research sites along an evapotranspiration gradient near Sterling, Stratton, and Walsh, Colorado. The sites have a 30-year history of dryland, no-till management, and are divided into different cropping system intensities that vary in the frequency of summer fallow periods in the rotation. Crop rotations studied here include wheat (*Triticum aestivum*)-fallow, wheat-corn (*Zea mays*) – fallow, and continuously cropped plots with small grains and forage crops including foxtail millet (*Setaria varidis*) and forage sorghum (*Sorghum bicolor*). Forage crop and wheat residues were tracked over two growing seasons (2015 and 2016) to estimate the length of time before soil surface cover fell below a 30% threshold and to create models for residue persistence. Decomposition Days (DD), a calculation that factors in temperature and rainfall to estimate cumulative conditions that favor decomposition, was used to normalize time scales following harvest across sites and years. Wheat residue covered 82% of the soil surface following harvest and summer forage crops covered 56%. Wheat persisted longer, taking 62.5 DD to fall to the 30% cover threshold, forage crop residue remained above the threshold for 16.6 DD. The decline of forage crop residue cover followed an exponential decay model. Wheat residue surface cover had a longer, slower decline and fit a quadratic decay model. Wheat stem heights were taller following harvest and heights declined at a similar or faster rate than forage crops. To assess rotation legacy impacts on soil erodibility, soils were sampled in May 2015 and tested for dry aggregate size distribution, dry aggregate stability, and carbon distribution by size classes and between cropping intensities. No differences were found in the amount of erodible aggregate size fraction (<0.84mm) by cropping system intensity. The site with the highest amount of clay in the soil displayed a significant difference in aggregate stability by crop rotation, with wheat-fallow rotations having stability of 2.96 ln J/Kg and continuously cropped systems having 2.80 ln J/Kg. Carbon distribution did not differ by crop rotation but did differ by size class at the site with the highest potential evapotranspiration and lowest clay content where the largest aggregates contained the highest proportion of carbon. Every phase (i.e., rotation year) of each of the crop rotation systems were represented each year. There was a significant difference in mean erodible fraction and aggregate stability by cropping phase at the time of sampling at the site with the highest clay content. Taken together, the crop residue and soil aggregate portions of the study indicate that the reliable and consistent prevention of wind erosion by crop system intensity may be more dependent upon annual crop residue surface cover than longer-term management impacts on soil aggregation properties. The differences in aggregate stability by crop type could be due to the impacts of active root systems at the time of sampling. More investigation is warranted into the influence of active root systems on macro dry aggregates and whether dry aggregate stability properties differ by season. Further study into the application of residue biomass decay models to residue soil cover, particularly in crops with multiple layers of residue is also indicated.

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Introduction

Wind flows through the history of the Great Plains of the United States. Homesteaders relished the moist breezes carrying the promise of rain and captured its power with windmills to pump groundwater for livestock and crops. They also cursed its capacity to bring locusts and destroy with tornadoes and blizzards. Wind supplied the villain for stories of easterners unprepared for the isolation of the Plains, unsettled by a land stretching to the horizon and driven mad by the sound of wind blowing in the wide grass sea. Supreme in the history and lore of wind on the Great Plains are the stories of the Dust Bowl, the time of economic and personal depression, a diminishing of communities, of farms and families as drought and wind destroyed the land.

Effects of the 1930s Dust Bowl era are still seen today on the plains. Abandoned sod houses crumble back to the earth as billboards request funds to restore stone schoolhouses that were once the pride of a community. Lands that were profitable in the heady 1920s then deserted when the forces of nature could not be overcome sit idle still. Old men in the local McDonald's in Lamar, Colorado, relate how their families barely survived and receive enthusiastically the researcher who says she works to understand wind erosion.

Wind erosion has reshaped topography and the fertility of the soil, not only historically but in the present day, though there have been improvements in reducing wind erosion rates in recent decades. The 1982 USDA-NRCS National Resource Inventory is used as the base from which to measure improvements in soil and water conservation efforts

(USDA-NRCS 2008). Between 1982 and 2010 soil lost to wind erosion was reduced from 1.38 billion tons per year to 740 million tons, a reduction of 46% (Baumhardt et al. 2015). Few recent studies have attempted to isolate the cost of wind erosion from other forms of soil degradation. Pimental et al. (1995) estimated that it led to over 9.6 billion dollars in off-farm property damage and health care costs annually in the US. On- farm costs of wind erosion include the need to replace soil nutrients removed with the erodible soil fraction, lower water infiltration, loss of water retention capacity, and reduce soil depth. These factors all result in reduced crop yields. While greater quantities of fertilizer and irrigation can be applied to the crop to mitigate the effects of soil loss in the short term, soil degradation has long-term impacts on agricultural productivity and on ecosystem services provided by the soil.

Early models of wind erosion included soil aggregate size, crop residue, and surface roughness as predictive factors (Chepil and Woodruff 1959). The Wind Erosion Equation developed by Dr W. S. Chepil of the USDA was published by Woodruff and Siddoway in 1965 after being modified due to updated research (Woodruff and Siddoway, 1965). The equation served to both assess a field's potential for soil loss and determine which field conditions could be changed to reduce erosion, though the complexity of the interactions between factors was not well captured in the equation (Woodruff and Siddoway, 1965; Tatarko et al. 2013). Simulation models to solve the Wind Erosion Equation were developed as early as 1970 (Fisher and Skidmore, 1970; Fryrear et al, 1998). The usefulness of being able to not only quickly determine the soil loss but also the ability to reverse the equation to assess necessary conditions for limiting soil loss was recognized as a benefit to computer-aided models (Fisher and Skidmore 1970).

Developed for use by the USDA NRCS for conservation planning, the Wind Erosion Prediction System (WEPS) from the USDA Agricultural Research Service (www.ars.usda.gov/research/software), uses a series of submodels such as management practices, hydrology, plant growth, and decomposition combined with climate and soil survey databases to predict soil loss (USDA-ARS 2016; Wagner 2013). Complex models such as WEPS are an improvement upon past equations that relied upon wind tunnel laboratory experiments, but the processes simulated must be validated to ensure accuracy. Field studies contribute to both the validation of current models and the development of new models. There is a need to validate WEPS and other models with a diverse array of management, climate, and soil types (Fryrear 1995). Though WEPS has been in use for some time, few validating field studies have been undertaken (Hagen 2004; Feng and Sharratt 2006).

Wind erosion can be prevented or limited by three methods: reducing wind speed, increasing soil surface cover, and having wind-resistant soils (Nordstrom and Hotta 2004; Borrelli et al. 2014). In agricultural systems, crop residues play a role in all three measures. Standing stems and residue pieces rising above the surface of the soil slow wind speeds. Residue layers directly blanket and protect surface soil aggregates. The addition of organic matter to the soil system by the above and belowground biomass of crops provides fodder for microbial-driven aggregation contributing to inherent erosion resistance.

A major development in the retention of crop residues on agricultural land in the western Great Plains was the movement towards reduced- and no-till management practices. The development of improved herbicides and herbicide tolerant crops by the 1980's made reductions in tillage for weed control possible (Unger and Skidmore 1994; Derpsch et al. 2010). The benefits of no-till production to the producer include reduced labor costs, improved soil structure, increased water use efficiency, higher yields in dryland systems, higher soil microbial biomass, and higher soil organic carbon (Hobbes et al. 2008; Triplett and Dick 2008; Lal 2015; Pittelkow et al. 2015). Without the burial of surface crop residues by tillage, soil is physically insulated from contact with wind. Studies comparing tillage to no-till have found that no-till systems reduce wind erosion susceptibility (Merrill et al. 1999; Triplett and Dick 2008; Gao et al. 2016). A small number of field studies (Schillinger 2016; Thorne et al. 2003) and few simulation studies (Wang et al. 2002, Nelson et al. 2015) have examined the impact of crop rotation within no-till systems on wind erosion.

The residues left on agricultural soils directly reduce wind erosion by protecting the surface and slowing wind speeds. For wind erosion prevention, soil surface area cover of 30% has been shown to prevent a majority of soil erosion, with only marginal improvements in soil loss prevention achieved with higher percentages of cover (Fryrear 1985). Standing height of residue is an additional factor in the reduction and prevention of erosion. While the surface they directly cover may be small, standing crop stems after harvest not only influence wind speed near the soil surface but also physically block the movement of soil particles (Steiner et al. 1994; Bilbro and Fryrear 1994; Jia et al. 2015).

Standing residue initially decomposes at a slower rate than residues in contact with the soil surface (Lyles and Allison 1981). Over time the roots and stem area in contact with the soil decompose and the weakened stems fall, becoming part of the pool of flat surface residues. Standing stems thus contribute to soil cover months after harvest.

Soil-inherent wind erodibility encompasses a variety of chemical, biological and physical soil characteristics which can be condensed into two representative and directly measurable components: aggregate size and dry aggregate stability (Zobeck 1991; Merrill et al. 1997). Essential for the formation of aggregates, carbon in agricultural systems is added to the soil system through root turnover, root exudates and crop residues. Soil organic carbon (SOC) has been shown to increase with increased cropping intensity in semi-arid environments (e.g., Campbell et al. 2005; Bowman et al. 1999). More intense rotations with less time in fallow can result in higher biomass production through positive system feedbacks of increased residues, improving soil carbon and limiting soil water loss (Sherrod et al. 2005; Cantero-Martinez et al. 2006). The retention of crop residues concentrates carbon near the soil surface, encouraging aggregation in the layer most necessary for wind erosion resistance (Baker et al. 2007; Plaza-Bonilla et al. 2013; Turmel et al. 2015).

The following two chapters detail the use of three long-term agricultural research sites to explore the interaction of crop rotation intensity, residue production, and wind erodibility.

The research can be divided into two sections, each guided by a question:

1: Do residues of different crop types influence temporal soil cover patterns?

2: Does crop rotation system impart long-term impacts on soil aggregation properties?

The investigation of the first question addresses two of the three modes of wind erosion mitigation: reducing wind speed and reducing wind contact with the soil surface. This was done by examining the temporal dynamics of residue cover over the 2015 and 2016 cropping seasons. The objectives for this portion were:

1) To quantify the soil surface covered by types of crop residues; and
2) To quantify the persistence of crop residue cover through time by crop type.

I hypothesized that residue cover would fit an exponential decay model and that soil cover would be higher and persist longer for winter wheat than summer annual crops.

The second question addresses the third mode of wind erosion mitigation: the resistance of the soil itself to wind erosion by fostering aggregation properties by carbon inputs from crop residues. This was done by analyzing soil samples taken in May of 2015. The objectives of this second portion of the study are:

1) Compare dry aggregate size distribution by cropping system intensity;
2) Compare dry aggregate stability by crop rotation intensity;
3) Examine organic carbon distribution between size classes; and
4) Compare soil carbon differences between cropping intensities.

I hypothesized that a history of continuous cropping would result in higher soil carbon, greater aggregation, and reduced erosion susceptibility relative to wheat-fallow rotations.

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Chapter 1: Crop Residue Cover Dynamics in Dryland, No-Till Systems

Introduction

Wind erosion is a key component of irreversible land degradation (Dregne 2002; Ravi et al. 2010). Wind erosion can be forestalled by three key factors: limiting wind speed, maximizing soil surface cover, and having wind-resistant soils (Nordstrom and Hotta 2004; Borrelli et al. 2014). Within annual cropping systems, tillage and crop residues are two major management practices that can influence wind erosion potential.

Tillage incorporates crop residues into the soil, burying them and exposing the soil surface, resulting in less soil protection (Lopez et al. 2003). Studies comparing tillage to no-till have found that no-till systems reduce wind erosion susceptibility (Merrill et al. 1999; Triplett and Dick 2008; Gao et al. 2016). Differing tillage methods and machinery result in varied amounts of residue incorporated into the soil and disruption of soil structure. Comparisons of soil properties between tilled systems and no-till have consistently displayed improvements in properties related to erodibility with no-till systems (Peterson, et al. 1998; Merrill et al. 1999; Lopez et al. 2003; Sparrow et al. 2006; Gao et al. 2016).

The quantity and physical structure of crop residues can play a role in all three key factors that influence wind erosion. Residue is the most basic physical deterrent to wind erosion, acting as a barrier as well as changing wind energy dynamics to reduce transport capacity (Hagen 1996). Maintaining crop residues also conserves water, adds carbon to the soil system, enhances microbial diversity and activity, fosters soil aggregation, and improves agricultural productivity (Lal 2015). An understanding of how to maximize production and minimize residue loss in cropping systems can inform management decisions to decrease wind erosion.

A protective layer of residue on the soil surface impedes wind contact and decreases wind speed near the surface. Maintaining a soil surface area cover of 30% has been shown to reduce soil erosion to tolerable levels, with only marginal improvements in soil loss prevention achieved with higher percentages of cover (Fryrear 1985). This cut-off of 30% is thus the threshold by which the USDA-NRCS, US Environmental Protection Agency and state extension services (EPA 2003; Lyon and Smith 2010) judge the success of a residue management scheme, particularly at the time points when wind magnitude is greatest.

Standing height of residue is an additional factor in the reduction and prevention of erosion. While the surface they directly cover may be small, standing crop stems after harvest not only influence wind speed at the soil surface but also act as snow intercepts, increasing soil moisture (Steiner et al. 1994). Standing residue characteristics that contribute to wind erosion mitigation include their height, diameter, and stand density. Standing residue initially decomposes at a slower rate than residues in contact with the soil surface (Lyles and Allison 1981). Standing residues eventually become part of the pool of surface residues as their roots and stems decompose and the stems fall.

Residue decomposition is regulated by a complex interplay of management choices and site characteristics. These components include but are not limited to: climate, crop type, growing conditions, residue composition and C/N ratio, residue size and surface area, and harvesting method. In general, residue decomposition rates increase in warm humid environments and when residues have lower C/N ratios, smaller size, and larger surface area (Steiner et al. 1999). Crop type and growing conditions, such as soil fertility levels, influence decomposition rates through differences in residue C/N ratios, biochemistry and stem height and density (Trinsoutrot et al. 2000). In no-till systems, crop residues can remain on the soil surface through the following year's crop growth and harvest, creating layers of residues over multiple years that can persist depending on weather conditions.

In the semi-arid High Plains, the traditional dryland (non-irrigated) wheat (*Triticum aestivum*)–fallow crop rotations incorporate fallow years to store water for the next season's crop. During the fallow period, fields are maintained as crop- and weed-free soil for 14 months following harvest, resulting in crop production for only 10 months out of every 24 months. Historically, tillage was used to control weeds during the fallow period, but tillage can decrease residue cover by breaking up and burying crop residues. The development of improved herbicides and herbicide tolerant crops made reductions in tillage for weed control possible by the 1980s (Unger and Skidmore 1994; Derpsch et al. 2010). Reductions in farm labor costs are a direct benefit of no-till production to the producer as well as the longer-term improvements in soil structure, increased water use efficiency, higher yields in dryland systems, and increased soil microbial biomass and soil organic carbon (Hobbes et al. 2008; Triplett and Dick 2008; Lal 2015; Pittelkow et al. 2015). With the increased adoption of no-till across the region, producers have increasingly intensified rotations to reduce the frequency of fallow. Rotations such as wheat-corn (*Zea mays*)-fallow or wheat-corn-millet (*Panicum miliaceum*)-fallow reduce fallow periods from 14 months out of 24, to 10-13 months out of 36 or 48 months (Farahani et al. 1998; Hansen et al. 2012).

There is a potential trade-off between available water and crop biomass production when intensifying cropping systems by reducing the frequency of fallow. In water-limited systems decreases in water storage due to intensified cropping or drought periods could result in less biomass production (Merrill et al. 1999). Increasing cropping intensity can reduce individual crop yields due to reduced soil moisture, which may limit or reduce residue returns and soil cover at key time points in the rotation cycle (Nielsen et al. 2016). More intensive no-till cropping systems involving less time in fallow may alternatively create positive system feedbacks through improved soil carbon and water storage (Sherrod et al. 2005). Shifting from wheat-fallow to continuous cropping, for example, can increase annualized biomass and residue production by producing an additional crop during the traditional fallow phase, possibly reducing soil evaporation and improving overall precipitation use efficiency (Cantero-Martinez et al. 2006).

Understanding the interwoven factors of climate, soil, and crops in the field can improve predictive agricultural models. Wind erosion models are by necessity developed primarily for application in dry and drought-prone regions and must be validated with field studies utilizing a variety of irrigation, tillage, and crop rotation practices. Historically, wind erosion models such as the Wind Erosion Equation (WEQ), which estimates average soil loss per year, were based on wind tunnel laboratory experiments and field tests (Woodruff and Siddoway 1965). These equations had a limited capacity to simulate the complex interactions between natural and management factors (Tatarko 2013). In 2010, the Wind Erosion Prediction System (WEPS) model replaced the WEQ. WEPS, which is publicly available online (www.ars.usda.gov/research/software). It uses a variety of submodels and databases in conjunction with field management operations to predict daily soil losses for specific fields or areas requested by the user (Wagner 2013).

Crop residue decomposition is one of the WEPS submodels. Residue characteristics that are strong predictors of erosion susceptibility simulated by WEPS include surface residue cover, standing stem height, stem diameter, and standing stem density. The WEPS model calculates residue biomass and surface cover daily from harvest date, using crop-specific decomposition rates and the effects of precipitation, air temperature, target yields, and management practices such as tillage (van Donk et al. 2017). There is a need to validate WEPS and other models with a diverse array of management, climate, and soil types (Fryrear 1995). Though WEPS has been in use for some time, few validating field studies have been undertaken (Hagen 2004; Feng and Sharratt 2006)

Fundamental to the understanding of the role residues play in reducing wind erosion risk is the accurate measurement of residue cover. Surface residue coverage can be indirectly estimated from residue mass. A common approach is to use this single time point measurement or estimate of residue mass then simulate residue decomposition dynamics over time using models rather than empirical measurements. A one-time sampling of residue mass may not automatically correlate to soil protection over time.

Temporal and spatial variability in residue persistence can impact the quality and effectiveness of soil cover. Residue dispersion following harvest is not uniform due to the unevenness of the soil surfaces and the effects of machinery (Allmaras et al. 1985, Fryrear 1985). Frequent visual assessments are time-and labor-intensive but are important for understanding the temporal dynamics of residue decay and movement. Time-course residue analyses provide important data for validating models such as WEPS.

A long-term cropping systems project, the Dryland Agroecosystem Project (DAP), was initiated in Eastern Colorado in 1985 to investigate the economic and agronomic implications of increasing crop rotation intensity in no-till systems. The rotation systems range along an intensity spectrum from wheat-fallow to continuous cropping. This study utilized the DAP to infer the susceptibility of crop rotation systems to wind erosion by examining the influence of different crop types on temporal soil cover patterns. The objectives were (1) to quantify the soil surface covered by types of crop residues and (2) to quantify the persistence of crop residue cover to the 30% threshold by crop type. I hypothesized that residue cover would fit an exponential decay model and that soil cover would be higher and persist longer for winter wheat than summer annual crops.

Materials and Methods

Site descriptions

The Dryland Agroecosystem Project (DAP) was established in 1985 by researchers at Colorado State University and USDA-Agricultural Research Service (ARS) to explore the various effects of crop rotation intensity in comparison to the traditional wheat-fallow systems of the Central High Plains under no-till management (Peterson et al. 1993). The DAP is comprised of three field sites in eastern Colorado representing an evapotranspiration gradient and the sites are referred to by the names of the nearest towns: Stratton, Sterling, and Walsh. For this study, only Stratton and Sterling sites were included due to crop failures at Walsh in 2015. Table 1.1 contains site characterization information, including precipitation, evapotranspiration, location, and soil properties.

Each study site is comprised of a catena with summit, sideslope, and toeslope positions. Only the summit areas at each site were included in this study since these areas are likely to be the most susceptible to wind erosion. All sites are dryland and no-till. Site strips were 6.1 m wide and the summits at least 46 m long. Fertilizer was applied at a rate of 45 kg ha^{-1} nitrogen (N) and 22 kg ha^{-1} P_2O_5 with wheat planting in 2013, 2014, and 2015. Sorghum and millet plots received 45 kg N ha^{-1} and 45 kg ha^{-1} P_2O_5 in the study years. Weeds were controlled throughout the growing season in both cropped and fallow strips with herbicides.

The rotations used in this study were wheat-fallow, wheat-corn-fallow, and continuously cropped grain-forage rotation (wheat-sorghum or wheat-millet) or forage-only rotation (sorghum-millet). Forage crops included forage sorghum (Sorghum bicolor) and foxtail millet (Setaria varidis). Continuous cropped strips have no summer fallow period and have a harvested crop every year. Rotations in the continuously cropped strips are not fixed and are managed to either maximize biomass production or to take advantage of expected weather and market opportunities. The crops in the continuous rotations during the study period of 2015 and 2016 included wheat and forage sorghum. For the fixed rotations, each phase (i.e., rotation year) of each rotation was represented every year and replicated twice. Use of these sites allowed for assessment of several crop residue types over the two years of the study. Corn was excluded from the study due to delayed planting in 2015 such that forage sorghum was planted in place of corn.

The wheat variety 'Byrd', was planted in October at 67 kg ha^{-1} on 30.5 cm row spacings. Forage sorghum variety 'Honey Sweet' and forage millet variety 'Golden German' were planted in early June at 13.5 and 11 kg seeds ha^{-1} respectively on 30.5 cm row spacings.

Sampling months (March to October) were selected to capture the growing season and time periods of greatest wind speeds and erosion susceptibility at these sites. The state of Colorado maintains automated weather stations throughout the state. The 20-year record of wind magnitudes at the three sites were highest in the spring (March-May) months (Iowa Environmental Mesonet, http://mesonet.agron.iastate.edu/info.php). Spring on the western plains has spotty snow cover and crops are either not well developed (wheat) or not yet planted (corn and forages), increasing the vulnerability to wind erosion. In Sterling, the highest daily wind speeds and least amount of calm occurred in April with average wind speeds of 5.6 m s^{-1}, gusts over 8.9 m s^{-1}, and only 5.4 % of the time calm. The station nearest to Stratton is Burlington, 20 miles away. The highest average daily wind speed in Burlington and the least calm periods also occurred in April. Gusts reached over 8.9 m s^{-1}, average wind speeds were 6.6 m s^{-1} and time with calm was 2.9%.

Residue Quantification

To track residue changes over time, flags were placed at two random spots on the summit portion of each study strip in March 2015. Every month from March through October of both 2015 and 2016 a quadrat measuring 1m x 0.8m was aligned with the flag and a picture taken with a camera on a tripod looking straight down from a height of 1.4m. Photographs were taken with a Panasonic DMC-FZ70 16.1 megapixel digital camera.

Photographs were organized by site and overlain with a 4 x 5 square grid (20 squares). Each square was visually assessed for the percentage covered by crop residue, weed residue, live crop and live weeds. The individual portions of the grid were scored for percentage of surface covered in 5% increments from 0-100%, with residue or live plant type receiving an individual score. Several people were trained to analyze the photos. Using the same protocol and cross-checking results provided us with consistent relative percent cover results across time and irrespective of who analyzed the photos. All photos were analyzed or checked by one person to further ensure a uniform application of the method. While there have been advancements in software for digital photograph analysis (Chen et al. 2010; Vanha-Majamaa et al. 2000), we selected manual image analysis due to the subtle color differences and shifting shadows between time points. Manual analysis also allowed for greater certainty in the distinct identification of crops and weeds.

Standing stems directly slow wind speeds. The number, height, and stem diameter of standing residues are used to calculate a vertical stem area index within the WEPS decomposition submodel (van Donk et al. 2017). For the further validation of the WEPS model, data was collected on stem heights and diameters. The average height of the residue was measured monthly through the two seasons. Within each quadrat, four crop residue heights were measured at random. Twice per growing season the number of standing residue pieces were counted and the diameter of 4 stems measured. Only pieces of crop residue at greater than a 10-degree slope were measured for height according to Steiner et al. (1994).

Tracking declines in crop residue cover in active agricultural systems is complicated by the growth of new crops and by weeds. One difficulty of the overhead picture method of assessing residue cover is that the surface crop residue cover can be concealed by live weeds, dead weeds, and growing crops. To minimize the effect of other covers obscuring crop residue, data from pictures with more than 20% cover by any other material were excluded from analysis of residue cover decomposition dynamics. This resulted in the exclusion of 30% of residue cover images. In total, 20% were excluded due to obscuring of residue by the next live crop and 10% of were excluded due to live weeds and weed residues. Analysis of the photo data showed that once live weeds or weed residues were over 20% in any plot, the crop residue surface cover would artificially decline then increase again once the weeds were terminated.

Decomposition Days

To normalize the time scale across sites and years, decomposition days were calculated as proposed by Steiner et al. (1999). Decomposition days are similar to growing degree days as an approach to standardizing decomposition conditions across time and location. The Decomposition Days (DD) equation used was developed by Steiner et al. 1999, in Bushland, TX and evaluated in eastern Oregon and North Dakota. This DD equation is used within the WEPS residue decomposition submodel. The equation relies on average daily air temperature and daily precipitation as factors that influence microbial activity that governs decomposition. Residue composition is another factor that can influence decomposition rate. The residues in this study were of varying crop types, measured over two years and two sites. We did not analyze residue quality as C:N composition of residue has been found to only have a major influence on decomposition rate for the two weeks following harvest (Gilmour 1998).

Ideal conditions for decomposition would occur with 32 deg C and at least 4 mm precipitation. Ideal conditions result in one DD, conditions less than ideal result in a fraction of a DD being added to the cumulative total days. Daily weather data was taken from the on-site CoAgMet stations (http://www.coagmet.colostate.edu/index.php). The weather station at Stratton had periodic missing data. In these instances, the weather station at Kirk 35.4km (22 miles) to the north was used.

The Decomposition Days were calculated as the lesser of a Temperature Coefficient and a Moisture Coefficient, neither of which can be greater than 1.

The Temperature Coefficient (TC) was:

$TC = (2T^2*(T_{opt}^2)-T^4)/ T_{opt}^4$

With T_{opt} = 32 degrees C and T = daily mean temperature

A precipitation coefficient (PC) was calculated based on an assumption of a minimum of 4mm precipitation necessary to wet a layer of residue:

PC = 1 if total daily precipitation is ≥4mm
PC = Precipitation/4 if total daily precipitation <4mm

And a Moisture coefficient (MC) constrained to ≤1:
$MC_t = MC_{t-1} + PC$
The DD has a limiting factor of either moisture or temperature, thus the lesser of the MC or TC each day is used.

Decomposition Days were accumulated following each harvest date until the planting of the next crop. Therefore, the earliest DD calculations began following 2013 crop harvests for cropping strips with fallow in 2014 and no harvested crop until 2015.

Data Analysis: Initial Crop Cover and the 30% Threshold

We used general analysis of variance (ANOVA) to test for main effects and interactions of site, year, and crop type or cropping system using JMP software v. 8.1. (SAS, Cary, NC, 2015). Corn planting was limited in the growing seasons studied and was removed from the analysis. We statistically compared residues by crop (wheat and forage) and mean Decomposition Days following harvest to initial residue measurement using pairwise t-tests of least square means. Forage sorghum and forage millet were grouped and analyzed together as forage crops.

A surface cover of 30% is generally accepted as the residue required to reduce wind erosion to 70% of that experienced by bare soil (Fryrear 1985). Using the statistical software R (version 3.2.4, 2016) and the plyr package, we created loess curves to model the decline of crop residue cover over time in each of the study site strips and to extract the mean DDs until residue reached the 30% cover threshold. The loess curves allow for estimating the point at which each strip reaches the 30% threshold within the existing data. The loess method does not assume a model and therefore cannot predict outside the data set. If a strip did not begin above 30% residue cover or if it did not fall to 30%, it was removed for this portion of the analysis. Differences in DD to reach 30% by crop were calculated using the ANOVA model as described above.

Data Analysis: Standing Stems

Stem counts and stem diameter measurements of each crop at each site were grouped by harvest year and by length of time after harvest that the measurement was taken. Stem count and stem diameter means and standard errors were calculated using JMP software. A site by cropping phase interaction ANOVA analysis was also performed on both stem counts and stem diameters.

Exponential curves were used to analyze the decline of wheat and forage crop residue heights for each harvest year at each site. Interactions of time (Decomposition Days) and crop type plus crop type and harvest year were analyzed at both sites.

Data Analysis: Modeling Crop Residue Cover Decline

To model the decline of crop residue cover, we created model curves for each site, strip, harvest year, and crop combination using the lsmeans, car, and lme4 packages in the statistical software R. We tested exponential decay and quadratic functions and compared R^2 and AIC (Aikaike Information Criterion) values to determine best model fit.

Results

The Decomposition Days (DDs) following harvest differed for each crop at each site. For example, wheat harvested July 15, 2015, in Sterling accumulated 9 DD in the 30 calendar days following harvest, millet harvested August 10, 2015, accumulated 5.5 DD in the 30 calendar days following harvest. The accumulation of Decomposition Days compared to calendar days can be seen for Sterling and Stratton in Figures 1.1 and 1.2.

Initial Crop Residue Cover and the 30% Threshold

Wheat residues from the previous harvest maintained greater soil cover than forage crops at the start of the growing season. After harvest in both growing seasons, wheat had 1.5 times higher residue cover than forage (Table 1.2, $p<0.0001$). The initial average wheat residue soil cover at both sites and both study years was 82% at 2 DDs after harvest and forage was 56% soil cover at 1 DDs.

Similar to the initial residue cover after crop harvest, the time as measured by DD until residue cover reached the 30% threshold for erosion susceptibility differed by crop (Table 1.3). Wheat took 3.8 times more DDs than forage to decline to 30% residue cover. At Sterling, several strips did not reach the 30% threshold before the next crop was established, indicating that our measurement of the number of DD using loess curves could be conservative.

Standing Stems

Stem count means for forage and wheat differed by crop at each site. The number of forage stems remaining after the 2015 harvest declined 20% at Sterling and 25% at Stratton between the 0-3 month post-harvest measurement and 6-8 months after harvest (Table 1.4). In the same period, the number of wheat stems declined 35% and 57% 0-3 and 6-8 months post-harvest, respectively. By the end of the next year's growing season following the September forage harvest, there were no forage stems that remained standing. Standing wheat stems declined 92% at Sterling and 94% at Stratton between the 6-8 month post-harvest measurement and the end of the following growing season.

Forage stem diameters were larger than wheat stem diameters at both sites in the period immediately following the 2015 harvest (Table 1.5). For crops harvested in 2015, forage stem diameter decreased 50% at Sterling and 32% at Stratton in the period between measurements taken 0-3 months after harvest and 12 months or more after harvest. In 2015, harvested wheat stem diameters declined 37% at Sterling and 27% at Stratton over the same timescale.

Standing Stem Heights

Wheat harvest produced taller initial residues compared to forage at both Sterling and Stratton (Figures 1.3- 1.6). This is not surprising considering the differences in standard cutting heights for wheat and forage crops. Wheat had a more rapid decline in standing stem heights over time. Both wheat and forage were fitted with an exponential decay line. In 2014 and 2015, Sterling showed high regression coefficients (R^2 = 0.72 and 0.81, respectively) for an exponential rate of stem height decline. At Stratton, wheat stem height declines fit an exponential curve (R^2 = 0.86 and 0.94) better than forage (R^2 = 0.50 and 0.57) in 2014 and 2015, respectively, and wheat stem heights declined at a faster rate than forage (Table 1.6). The rate of decline did not differ by crop type at Sterling.

Modeling Crop Residue Cover Decline

An exponential decay model is often used for decay of residue biomass models (Steiner et al. 1999; Ruffo and Bollero 2003; Quemada 2004). This decay model was tested for both wheat and forage crops at both sites. Because the residue decomposition model fits did not differ by site, data from both sites were analyzed together. Both forage and wheat residue decay models followed similar patterns at the Sterling and Stratton sites (Figs 1.7 and 1.8, and A.1).

We hypothesized that residue cover over time would also fit an exponential decay model. This model fit the decline of forage residue cover at both sites (Table 1.7, Fig 1.7) demonstrating the rapid decline of forage residue cover from the initial post-harvest amount and the concave shape of the data (Fig 1.7). While the exponential decay model was the best fit for forage, it was not a good fit for wheat residues so an alternative model was derived that had a better fit (Table 1.8, Fig 1.8). A quadratic model better represented the endurance of wheat residue cover after harvest at both sites and the convex shape described its long, slow decline (Fig 1.8).

Discussion

In this study, wheat consistently produced more residue cover immediately after harvest, cover that also persisted almost 2-fold longer than forage crop residues. Initial residue cover produced by wheat was 1.5 times greater than that produced by forage sorghum or forage millet. Forage residue cover remained for 17 DD, or approximately 8-9 months in the eastern Colorado climate before falling to the 30% threshold. Wheat cover endured 63 DD or about 14-15 months in this climate before reaching the threshold. Forage residue cover would fall below 30% soil cover before the crop planted the following year could reach a stage of growth large enough to provide the 30% threshold of surface cover. Wheat residue would remain protective of the soil through the next growing season in continuously planted systems. In wheat-fallow systems wheat residue cover would fall to less than 30% in approximately 14 months, near the planting of the following wheat crop. The residue would provide sufficient cover for the fallow phase during the vulnerable spring wind erosion season. However, from planting until the wheat crop provides total cover > 30%, the field may be vulnerable to wind erosion. Given the post-harvest amount of wheat residue cover and its persistence over time, wheat-based rotations may provide more enduring wind erosion protection for the soil compared to rotations based in summer annual crops, such as corn or forages.

Use of non-linear, loess curve fitting to determine time to the 30% cover threshold, while valuable, did limit the number of wheat strips included. Several of the strips could not be evaluated because they remained above 30% cover for the length of the study. Including a longer time period in future studies would improve the estimate of wheat residue persistence.

The crop type differences we found were likely influenced more by the physical stem density, height, stem diameter (i.e., stem area), and biomass production due to differences in seeding rates and row spacings rather than fundamental differences in plant residue biochemistry. Plant biomass composition has been found to not influence decomposition rate after the first two weeks following harvest (Gilmour 1998), where residue cover decline after this period should be dependent on weather and the size, amount, and distribution of both flat and standing residue. The use of a Decomposition Days equation to standardize time scales across years and sites and accounts for the impact of weather on the rate of residue decline. Understanding the other factors of size, amount, and distribution of crop residues requires thorough field research at multiple sites over multiple years.

The adoption of no-till management in the western Great Plains has often been accompanied by an increase in cropping intensity and the addition of summer annual crops such as corn and forages (Farahani et al. 1998; Hansen et al. 2012). Diversification of crops from the strict wheat-fallow system has reduced financial risk for producers and increased water use efficiency in these water-limited systems. The lower amount of crop biomass remaining in the field following harvest of summer annual crops may however have negative consequences for wind erosion protection. The most vulnerable point in these intensified rotations is likely during the shortened fallow period after a summer crop and preceding the next winter wheat crop. Some producers in the region are eliminating this fallow period all together with several potential benefits, including increased soil carbon and reduced herbicide inputs (Rosenzweig et al. 2018). However, even continuous cropping systems may be vulnerable to erosion in early spring between summer annual crops such as forage sorghum, millet, or corn.

Past studies have described residue decline with an exponential decay model. Those studies generally rely on measurements of residue mass following harvest and residue mass samples throughout the growing season (Ruffo and Bollero 2003; Steiner et al. 1999), or surface litterbags (Quemada 2004). Crop residue cover, however, is a direct barrier to wind erosion, protecting the soil surface from wind contact and slowing wind speeds. Direct measurements of surface residue cover are less common. Taking these measurements is time and labor intensive, requiring sampling at regular intervals.

The use of visual assessment of monthly photographs of surface cover and standing stem heights, while time and labor intense, provided a consistent method for assessing the decline of residue cover and stem heights. Other methods of quantifying residue cover such as line transect are possible but have limitations. The line transect method only accounts for flat, surface-touching residue, not the protective capacity of near-surface residues such as standing or leaning stems. Variations in natural light can be a hinderance to automated analysis of field photographs (Yu et al. 2017). Vegetative cover in multiple layers and with multiple species can reduce the accuracy of automated image analysis (Vanha-Majamaa et al. 2000). Visual assessment rather than software analysis of the photographs allowed for distinctions in shadows and shadings. Further, the first-hand knowledge of the field conditions at each sampling made identification of weeds and crops more accurate, which could have been an obstacle to automated assessment approaches. Current plant image analysis software options do not include software designed to identify residues, which can be difficult to distinguish from soil (Lobet et al. 2013). The photographs are part of the record of the long-term Dryland Agroecosystem Project and can be used as training materials for future research at these sites and others.

Surface cover estimates built on biomass decay models may not fit surface cover decline for several reasons. Residues may decrease in mass for a period of time while retaining surface area. The initial depth of the residue can consist of several layers of material. Layers in contact with the soil surface will decay whilst leaving the amount of soil covered unchanged. Measurements used in calculating biomass production and soil carbon inputs may not be appropriate for calculating vulnerability to wind erosion. Surface litterbags are not subject to movement by wind and water over time as individual pieces of residue are. Development of models specific to surface cover decline would be valuable to erosion research.

The impact of weeds on soil moisture and temperature can also be an issue in agricultural systems. The WEPS model currently assumes weeds are controlled. The timing and biomass of weed growth can influence crop production and wind erosion potential, though the soil surface protection by weeds has not been well studied (Mendez et al. 2015). Weed growth additionally intercepts rain, shades the soil, and removes water from the system and some weeds may have a competitive advantage in no-till systems (Hansen et al. 2012). The amount of weeds in the plots of this study limited the number of plots for which photographs could be accurately assessed for crop residue cover. While weed dynamics are rarely included in models due to their high variability, including an option for including weed cover estimates for a given site in future versions of WEPS would move the model closer to the experiences of producers.

The WEPS residue decomposition submodel retains sequential pools of residue through successive harvests (van Donk et al. 2017). Collecting data on crop residues from former harvests while subsequent crops are growing is more difficult than quantifying crop residues on fallowed fields but is an important component of fully understanding residue dynamics. Few studies have continued to examine crop residues through subsequent growing seasons as new crops develop (Cantero-Martinez et al. 2006). This study continued quantifying residue cover until the following crop was harvested or until the surface was fully covered by growing live crop. More multi-year studies into the decline of residue cover while new crops are growing as well as during fallow periods are needed.

Wind erosion remains an issue affecting the arid and semi-arid regions of the world, causing irreversible soil degradation. An understanding of the manner and timescale in which crop residue cover declines can aid in refining models for erosion prediction and provide practical knowledge for erosion prevention. The hypothesis that soil residue cover would be higher and persist longer for winter wheat than summer annual crops was supported in this study, with wheat providing greater cover immediately after harvest and for a longer duration. The hypothesis that residue cover would fit an exponential decay model was supported for forage sorghum and forage millet, but not for wheat over the course of this study. Further investigation is needed into whether the quadratic decay model holds for wheat residue cover decline over longer time periods and in other climates. The delayed decline in wheat residue coverage relative to summer annual forage crops supports the use of wheat-based rotations for increasing protective crop residues and reducing wind erosion susceptibility.

Table 1.1. Historical annual precipitation (30-year average), average growing season open pan evaporation (March to October), soil texture and classification for the summit slopes, and annual precipitation during the study from the Dryland Agroecosystem Project (DAP) sites near Sterling and Stratton, Colorado. Adapted from Peterson, et al. (2001) and Cantero-Martinez et al. (2006).

Site	Location	Elevation Ft (m)	Historical Average Annual Precipitation (mm)[a]	Open Pan Evaporation (mm) (March-October)	Annual precipitation during study (mm)[a]	Soil Type	Surface 10 cm Soil Texture	Soil Classification
Sterling	40.37° N 103.13°W	4400 (1341)	440	1600	433(2014) 510(2015) 364(2016)	Loam	Clay: 21% Silt: 34% Sand: 45%	Fine-silty, mixed, mesic Aridic Argiustoll
Stratton	39.18° N 102.26°W	4380 (1335)	415	1725	357(2014) 331(2015) 286(2016)	Clay Loam	Clay: 34% Silt: 41% Sand: 25%	Fine-silty, mixed, mesic Aridic Argiustoll

[a] Study year in parentheses. Historical and study year precipitation data from CoAgMet (http://www.coagmet.colostate.edu/index.php). Stratton data taken from nearby Kirk site due to missing data from Stratton CoAgMet station during study period.

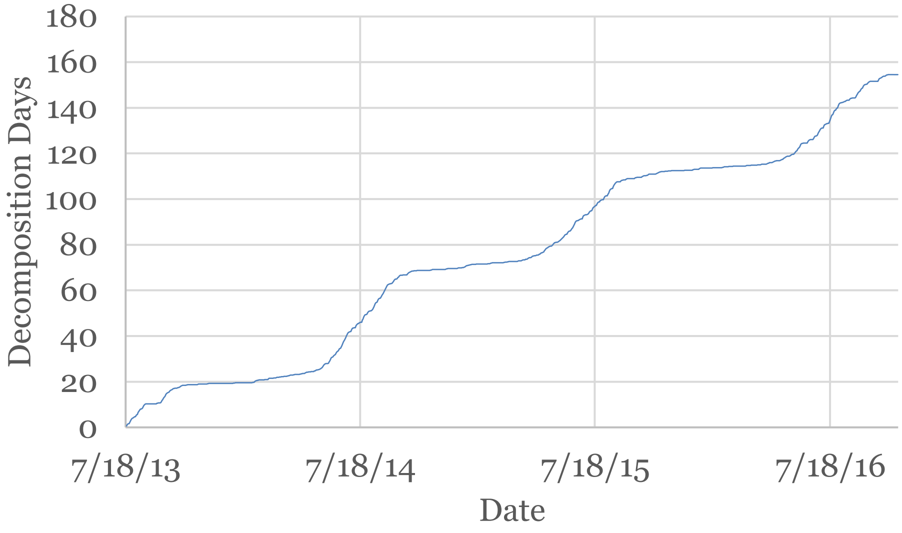

Figure 1.1: Cumulative Decomposition Days in Sterling, Colorado beginning after wheat harvest 2013.

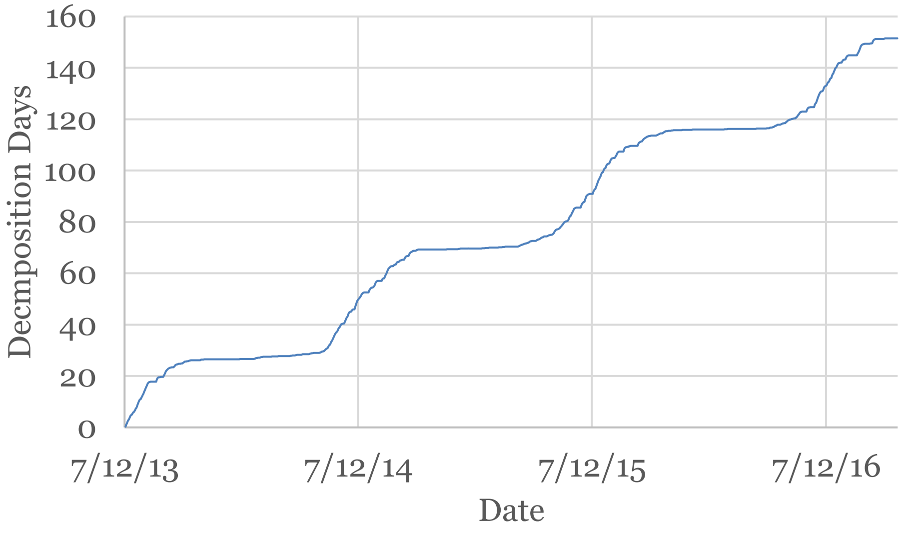

Figure 1.2: Cumulative Decomposition Days in Stratton, Colorado beginning after wheat harvest 2013.

Table 1.2. Initial crop residue cover within the month of harvest for forage sorghum, hay millet, and wheat at each site and the least squares means after accounting for harvest year and site. Different letters represent significant differences within a column ($p<0.05$). Standard errors are in parentheses.

Harvest Year	**Site**	**Crop**	**Initial Mean % Crop Residue Cover (SE)**	**Mean Decomposition Days**
2015	Sterling	Forage	59.3 (7.5)	0
2016	Sterling	Forage	39.0 (10.0)	0
2015	Stratton	Forage	65.5 (3.5)	0.05
2016	Stratton	Forage	54.0 (8.2)	4.6 (0.5)
2015	Sterling	Wheat	74.8 (7.5)	0
2016	Sterling	Wheat	80.4 (4.1)	0
2015	Stratton	Wheat	75.4 (6.5)	6.4
2016	Stratton	Wheat	97.9 (1.5)	2.2
Mean		**Forage**	**56 (4) b**	**1.10 (0.3) b**
Mean		**Wheat**	**82 (4) a**	**2.05 (0.3) a**

Table 1.3. The mean decomposition days for crop residue cover to fall to 30% following harvest by harvest year and site for forages sorghum and millet and for wheat with the least squares means comparison by crop. Standard errors are in parentheses.

Harvest Year	**Site**	**Crop**	**Decomposition Days to 30% Cover**
2014	Sterling	Forage	16.09 (2.2)
2015	Sterling	Forage	17.17 (9.0)
2014	Stratton	Forage	15.90 (2.3)
2015	Stratton	Forage	16.87 (4.2)
2014	Sterling	Wheat	68.08 (0)
2015	Sterling	Wheat	58.84 (0)
2014	Stratton	Wheat	65.98 (0.5)
2015	Stratton	Wheat	54.31 (0)
Mean		**Forage**	16.6 (2.3) b
Mean		**Wheat**	62.5 (4.3) a

Table 1.4: Stem count means by months after harvest. Means are standing stems per m^2. Standard errors are in parentheses.

Harvest Year	Site	Crop	0-3 months	6-8 months	12+ months
2014	Sterling	Forage	.	47.25 (9.6)	0 (0)
2015	Sterling	Forage	43.63 (5.5)	34.75 (5.5)	.
2014	Stratton	Forage	.	27.5 (4.6)	0 (0)
2015	Stratton	Forage	47.88 (0.13)	35.88 (4.9)	.
2014	Sterling	Wheat	.	462.63 (69.6)	34.88 (3.8)
2015	Sterling	Wheat	72.5 (8.4)	47.13 (5.6)	.
2014	Stratton	Wheat	.	353.25 (68.8)	21.25 (10.8)
2015	Stratton	Wheat	143.75 (31.6)	61.875 (18.1)	.

Table 1.5: Standing stem diameter means (cm) by months after harvest. Standard errors are in parentheses.

Harvest Year	Site	Crop	0-3 months	6-8 months	12+ months
2014	Sterling	Forage	.	1.06 (0.07)	.
2015	Sterling	Forage	1.05 (0.08)	0.53 (0.06)	.
2014	Stratton	Forage	.	0.85(0.11)	.
2015	Stratton	Forage	.73(0.05)	0.50 (0.06)	.
2014	Sterling	Wheat	.	0.35 (0.04)	0.28 (0.04)
2015	Sterling	Wheat	0.40(0.04)	0.25(0.02)	.
2014	Stratton	Wheat	.	0.23(0.01)	0.22(0.2)
2015	Stratton	Wheat	.30(0.003)	0.22(0.01)	.

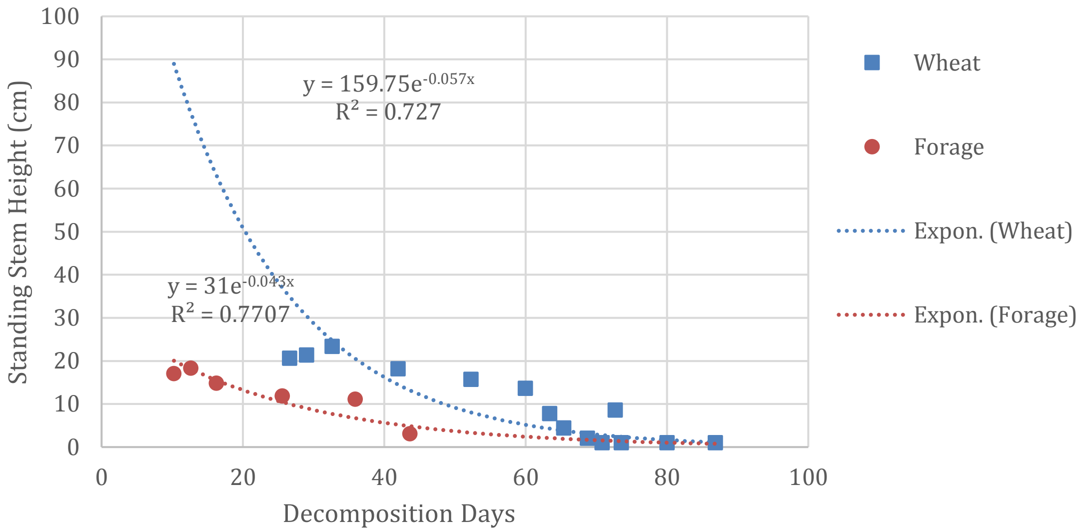

Figure 1.3: Decline of standing residue heights at Sterling 2014 with fitted exponential decay lines for both wheat and forage.

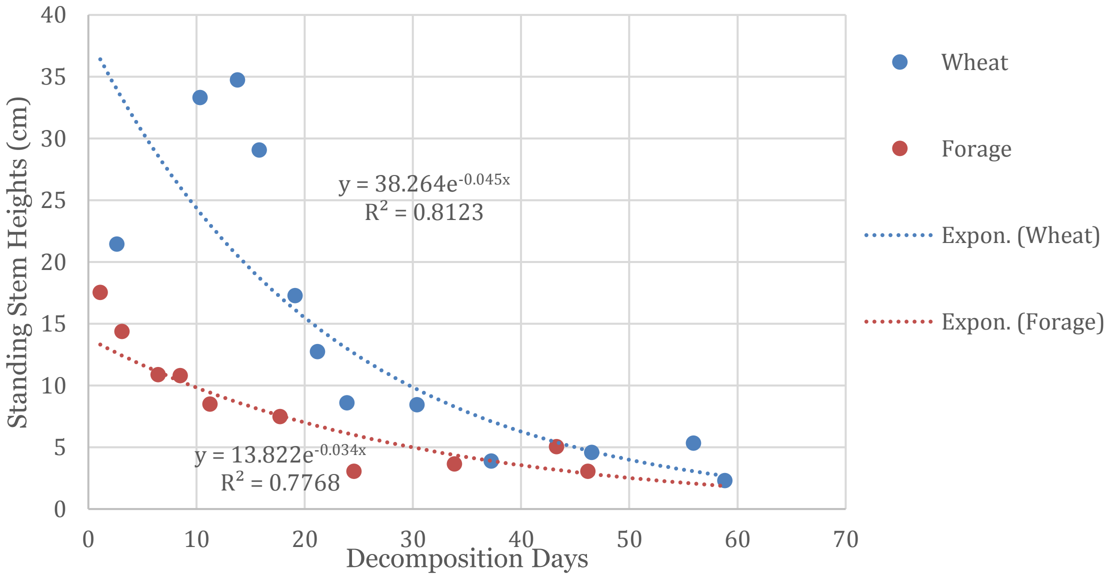

Figure 1.4: Decline of standing residue heights at Sterling 2015 with fitted exponential decay lines for both wheat and forage.

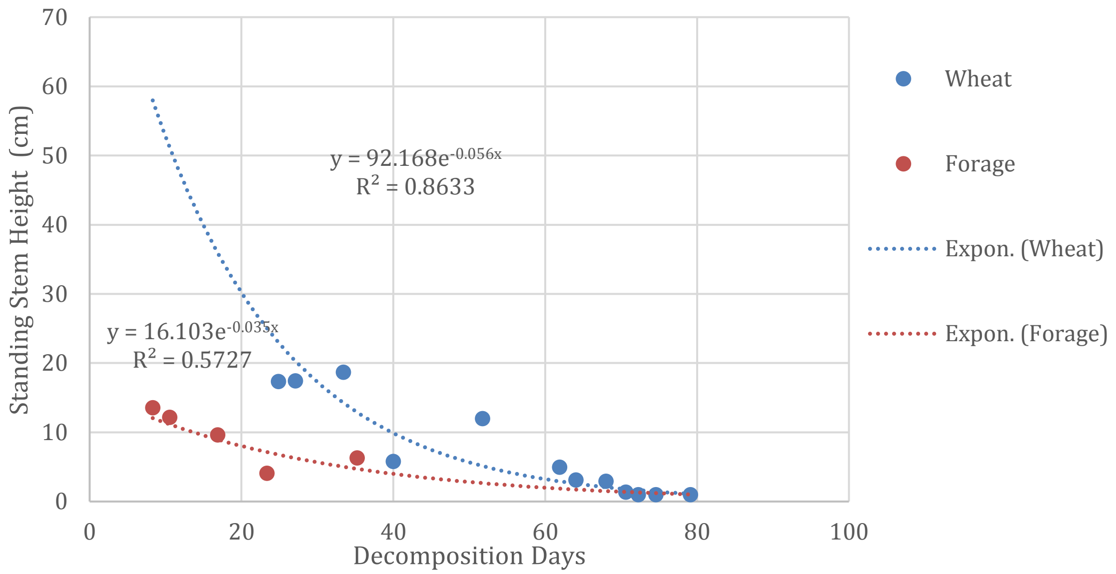

Figure 1.5: Decline of standing residue heights at Stratton 2014 with fitted exponential decay lines for both wheat and forage.

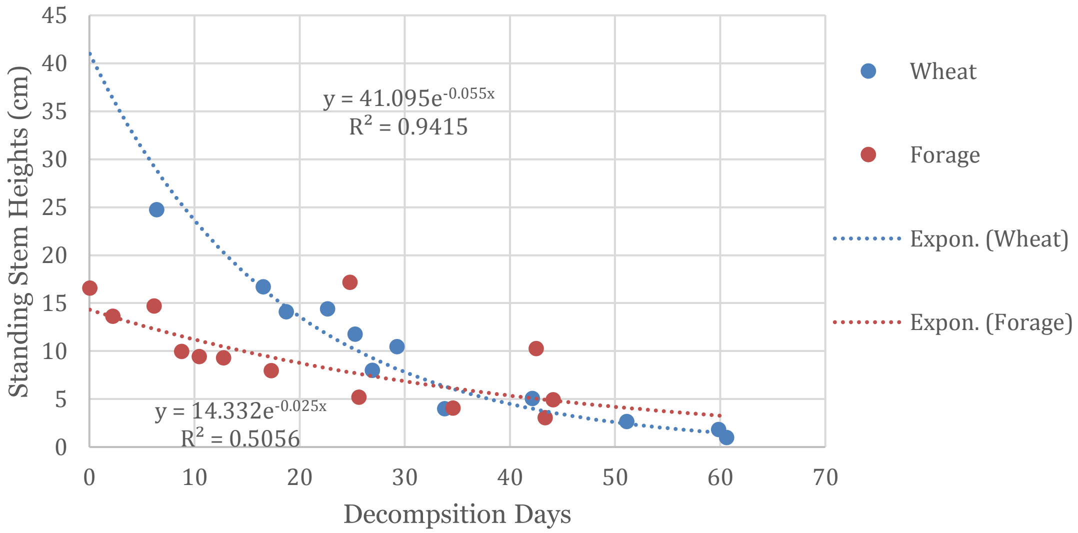

Figure 1.6: Decline of standing residue heights at Stratton 2015 with fitted exponential decay lines for both wheat and forage.

Table 1.6. Analysis of crop residue height declines for 2014 and 2015 at Sterling and Stratton as affected by decomposition days, crop type, year, and their interactions.

		Estimate	**Sum of Squares**	**F Ratio**	**Prob > F**
Sterling					
	Decomp Days	-0.05	176.9	341.4	< 0.0001
	Residue Crop (Forage)	-0.53	79.1	152.7	< 0.0001
	Harvest Year	-0.54	36.9	71.2	< 0.0001
	Decomp Days* Residue Crop	0.001	0.13	0.25	0.62
	Harvest Year* Residue Crop	0.19	4.39	8.5	0.004
Stratton					
	Decomp Days	-0.04	129.5	247.1	< 0.0001
	Residue Crop	-0.33	28.9	55.2	< 0.0001
	Harvest Year	-0.22	4.9	9.3	0.0024
	Decomp Days* Residue Crop	0.01	11.1	21.3	< 0.0001
	Harvest Year* Residue Crop	0.11	1.4	2.8	0.0979

Table 1.7. Model parameters and R^2 values for exponential decay of forage residue surface cover over time at each site. Standard errors of model parameters are in parentheses.

Site	**Mean B_0 (SE)**	**Mean B_1 (SE)**	**R^2 (SE)**
Sterling	77.0 (10.4)	-0.05 (0.01)	0.69 (0.07)
Stratton	71.7 (7.3)	-0.30 (.24)	0.59 (0.08)
Mean	**74.3 (6.2)**	**-0.18 (0.12)**	**0.64 (0.05)**

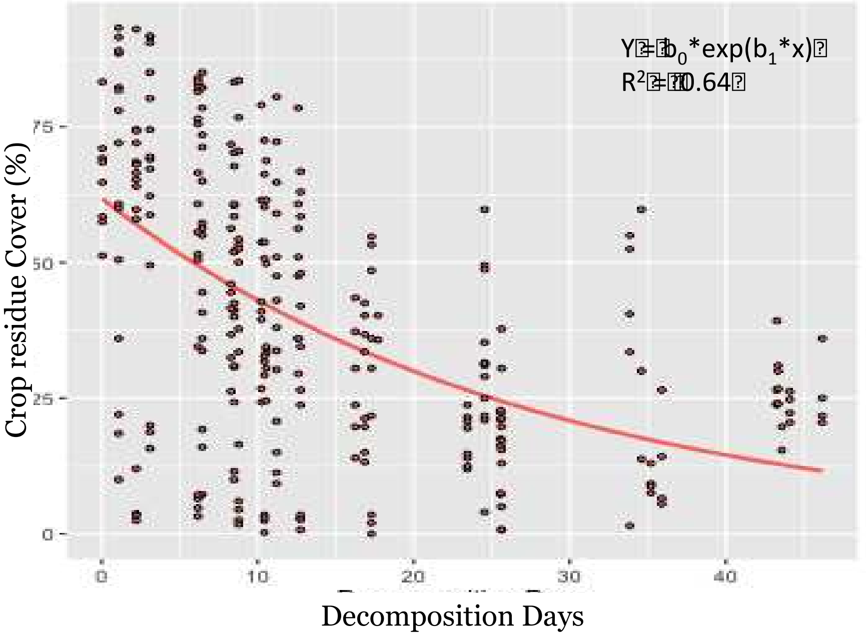

Figure 1.7. Exponential decay model for decline of forage residue cover for Stratton and Sterling sites. Each point represents the data from one photograph of soil surface cover.

Table 1.8. Model parameters and R^2 values for quadratic decay of wheat residue surface cover over time at each site. Standard errors of model parameters are in parentheses.

Site	**Mean B_0 (SE)**	**Mean B_1 (SE)**	**Mean B_2 (SE)**	**Mean R^2 (SE)**
Sterling	61.70 (10.09)	1.82 (0.49)	0.03 (0.02)	0.71 (0.05)
Stratton	93.02 (22.90)	1.91 (1.23)	0.05 (0.01)	0.69 (0.08)
Mean	**80.12 (14.28)**	**1.87 (0.74)**	**0.04 (0.01)**	**0.70 (0.05)**

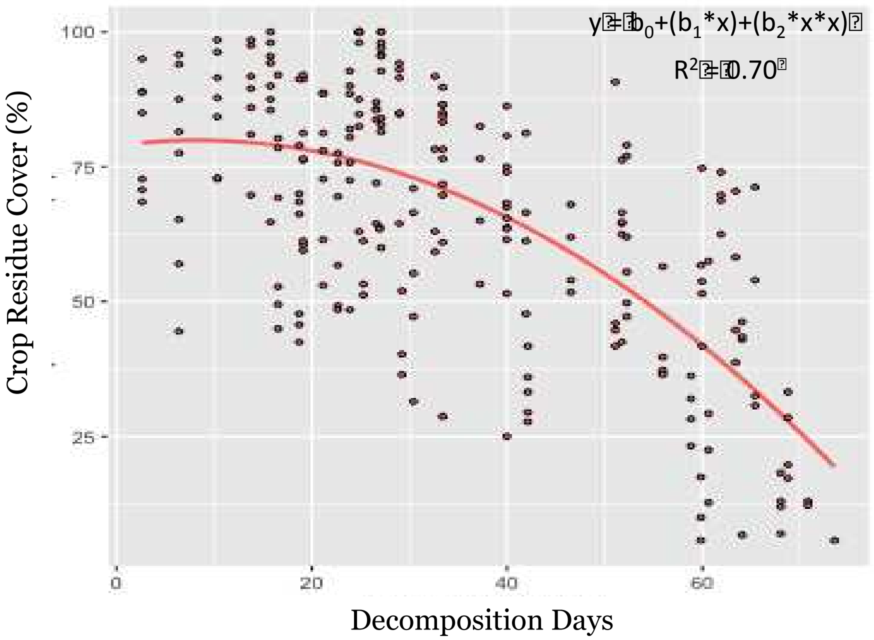

Figure 1.8. Quadratic model fit for wheat residue cover decline for Stratton and Sterling sites. Each point represents the data from one photograph of soil surface cover.

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Chapter 2: Effects of Cropping Intensity on Soil Erodibility in Dryland No-till Systems

Introduction

Wind erosion can greatly influence the productivity of arid and semi-arid agricultural systems. The effects of soil loss can include decreased yields, lower water infiltration and retention rates, and decreased soil nutrients (Verity and Anderson 1990). On the Great Plains of the United States, wind erosion can regularly remove up to 6 Mg ha^{-1} year^{-1} and as much as 18 Mg ha^{-1} year^{-1} of soil (Hansen et al. 2012). The essential factors in limiting wind erosion are reducing wind speed, maximizing soil surface cover, and having erosion-resistant soils (Nordstrom and Hotta 2004; Borrelli et al. 2014).

No-till systems can decrease wind erodibility by several mechanisms. Cover of the soil by crop residue is the most recommended physical deterrent to wind erosion, acting as a barrier as well as changing wind energy dynamics to reduce transport capacity (Hagen 1996). Within annual cropping systems, tillage or residue decomposition can leave the soil with little or no cover for time periods. Within forage or bioenergy systems, removal of residues can also increase the risk of wind erosion (Miner et al. 2013). The spring on the western plains is a high-risk time period for wind erosion due to strong winds and spotty snow cover protection. Crops are also either not well developed or not yet planted, and the previous crop's residue may have been buried by tillage, decomposed or blown away. In agricultural systems, management legacies influence soil properties through physical impacts to the soil. The absence of residue cover affects the degree to which soil physical properties are susceptible to wind erosion. Tillage mechanically breaks soil structure and encourages the mineralization of organic carbon by microbes, accelerating the breakdown of aggregates (Blanco-Canqui and Lal 2004; Six et al. 2002). Reducing tillage has been shown to improve soil aggregation, increasing both size and stability (Álvaro-Fuentes et al. 2008; Blanco-Canqui and Lal 2004). The size and stability of aggregates are key predictors of erosion susceptibility (Tatarko 2001).

Cropping system intensities and crop rotations add differing amounts of carbon to the soil in the form of crop residues. More intensive no-till cropping systems involving less time in fallow may create positive system feedbacks through increased residues, improving soil carbon and water management. Shifting from wheat-fallow systems to continuous cropping, for example, can increase annualized biomass and residue production which may limit the loss of soil moisture between cropping seasons (Cantero-Martinez et al. 2006)

Past research, including research at the sites used in this study, has shown increases in soil carbon with increased cropping intensity in the semi-arid Great Plains (Campbell et al. 2005; Sherrod et al. 2003). Greater biomass production leads to higher soil carbon inputs and increased aggregation. Aggregates and carbon are intrinsically tied together as aggregates physically protect carbon from microbial consumption and aggregates are formed partially by the adhesive properties of microbial by-products during organic matter decomposition (Blanco-Canqui and Lal 2004; Six et al. 2000).

Soil-inherent wind erodibility can be narrowed to two essential aggregate-related properties: the size (aggregate size distribution) and strength of soil aggregates (dry aggregate stability) (Merrill et al. 1999). Soil aggregates less than 0.84mm in diameter have been shown to be the most vulnerable to wind displacement due simply to their size and mass (Chepil 1958) and are referred to as the erodible fraction. Dry aggregate stability is a measurement of the external forces required to destroy a soil aggregate. Stability can change over time with the influences of management, including residue and cropping practices, and climate (Abivena et al. 2009). Aggregates with greater stability are better able to resist the forces of abrasion by wind-driven particles and debris.

The Wind Erosion Prediction System (WEPS; www.ars.usda.gov/research/software) was developed by the United States Department of Agriculture to model erosion from agricultural fields for conservation planning purposes (Wagner 2013). Integrated into the overall model are a series of submodels simulating soil, water, management, and plant processes informed by databases and user inputs including field information and management practices (USDA-ARS 2001; Wagner 2013). Soil properties such as aggregate size distribution and aggregate stability are estimated within WEPS and are principal features to the model (Zobeck 1991). As the influences of crop rotation intensity on soil properties has not been well reported (Feng et al. 2011) and WEPS model could benefit from additional validation through a spectrum of climates, soil types, and management decisions (Fryrear 1995), this study seeks to add to the body of research informing the WEPS program.

While there has been extensive research evaluating wind erosion susceptibility under different tillage regimes, less is known about cropping system legacy impacts on erosion susceptibility under no-till management. The question guiding our research was: Does rotation legacy impact wind erodibility via changes in soil properties? Using a 30-year no-till dryland cropping systems experiment, we evaluated cropping system effects on (1) dry aggregate size distribution (2) dry aggregate stability (3) carbon distribution between size classes and (4) soil carbon differences between cropping intensities. We hypothesized that the more intense cropping systems would lead to higher rates of soil carbon, greater aggregation, and therefore, reduced wind erosion susceptibility when compared to wheat-fallow rotation systems.

Materials and Methods

Site Descriptions

The Dryland Agroecosystem Project (DAP) was established in 1985 by researchers at Colorado State University and USDA-ARS to explore the various effects of crop rotation intensity in comparison to the traditional wheat-fallow systems of the Central High Plains (Peterson et al. 1993). The DAP is comprised of three dryland, no-till field sites in eastern Colorado. The sites represent an evapotranspiration gradient and are referred to by the names of the nearest towns, Walsh, Sterling, and Stratton. (Table 2.1). Each study site is comprised of a catena, however only the summit areas at each site were included in this study since these areas are likely the most susceptible to wind erosion. The sites have varying soil texture within the surface 10 cm with Walsh having the lowest amount of clay (17%) and Stratton the highest (34%; Figure 1.1). The results of this study are presented in order of increasing soil clay content (i.e., Walsh, Sterling, Stratton).

The rotations used in this study were: (1) wheat-fallow (*Triticum aestivum*), (2) wheat-corn-fallow (*Zea mays*), and (3) continuous cropping. Continuous rotations included annual grain crops and forage crops such as foxtail millet (*Setaria varidis*), forage sorghum (*Sorghum bicolor*), and forage soybean (*Glycine max*) (Table 2.2). The continuously cropped rotations are managed to either maximize biomass production or to take advantage of expected weather and market opportunities. To demonstrate the relative productivity of each site, the 30-year average yields for the summit position for each of the crops is presented by crop rotation system in Table 2. Site strips are 20 ft (6.1m) wide and the summits at least 150 ft (45.7 m) long. Each phase (i.e., rotation year) of each rotation was represented every year and replicated twice.

Aggregate Size Distribution and Geometric Mean Diameter

In May of 2015, approximately 2 kg soil samples were collected from each strip to a depth of 5cm with a flat shovel. Samples were air dried at room temperature for several weeks, then a rotary sieve with graduated sections was used to divide the sample by size class (Chepil 1962; Lyles et al. 1970). The size classes resulting from the rotary sieve were <0.42mm, 0.42-0.84mm, 0.84-2mm, 2-6.35mm, 6.35-14.05mm, 14.05-44.45mm, and >44.45mm. To simplify, results of some size classes were combined, resulting in the size classes 0 – 0.84 mm, 0.84 – 2 mm, 2 – 6.35 mm and greater than 6.35 mm being used in this study. The smallest size class is considered the erodible fraction of the soil (Chepil 1958).

Geometric mean diameter (GMD) is calculated from the mean diameter of each size fraction and the proportion of the weight of the total sample contained within each size fraction according to Wagner and Ding, 1994. GMD provides a single-number point by which to compare soil aggregate size distributions (Tatarko 2001, Feng et al. 2011),

Dry Aggregate Stability

Also, in May of 2015, another set of soil samples from each strip were taken to a depth of 5 cm with a flat shovel and gently sieved in the field with a 50 mm opening sieve to remove smaller aggregates. Aggregates approximately 5 cm in diameter were collected from the screen. After air drying at room temperature, samples were processed with a Soil Aggregate Crushing Energy Meter (Boyd et al., 1983). Near ellipsoid-shaped aggregates approximately 4cm long and 3cm high were placed between two plates that were forced together and the applied force was measured.

As the plates come together crushing the sample, the force increases. The sample will break, triggering a release in force. When the force applied drops by at least 25% it is recorded as the initial break force. Pressure is continually applied until the force on the sample is 1.5 times greater than the previous high point. The energy required is calculated as the area under the curve from the initial break force to the end point along the vertical displacement distance. Forces are reported in newtons and energy reported in joules. The stability in J kg^{-1} were calculated for each of 30 aggregates per strip and then the natural log of those are averaged.

Soil Moisture

Soil samples of 8 composite 2-cm cores per strip were taken with a soil corer to a depth of 5 cm, collected the same day as the samples for aggregate size, aggregate stability, and soil carbon. Samples were weighed, dried for 72 hours in a 105° C. oven and weighed again. The gravimetric soil moisture content was calculated as (moist soil mass – dry soil mass) / dry soil mass.

Carbon Analysis

For total carbon analysis by rotation treatment, soil samples of 8 composite 2-cm cores per strip were taken with a soil corer to a depth of 5 cm. Samples were air-dried and roller-ground before total carbon was determined using a LECO elemental analyzer (LECO Corp. St Joseph, MI). The inorganic carbon content of each sample was measured by pressure-calcimeter method according to Sherrod et al. (2002) and subtracted from total carbon to calculate soil organic carbon.

For carbon analysis by aggregate size, a subsample of each rotary sieve size class from each plot was roller-ground. The aggregate size classes analyzed were <0.84mm, 0.84–2mm, 2-6.35mm, and >6.35mm. Roots and liter were removed from all samples. Total soil carbon for all samples was determined by combustion with a LECO elemental analyzer (LECO Corp. St Joseph, MI). Inorganic carbon was determined by pressure-calcimeter method (Sherrod et al. 2002) and subtracted from total carbon to obtain soil organic carbon.

Statistical Analysis

We used analysis of variance (ANOVA) to test for main effects and interactions of site and crop rotation treatment intensity on mean erodible fraction, geometric mean diameter, and aggregate stability. ANOVA was also used to test for main effects and interactions between site and crop phase at the time of sampling. For organic carbon concentration, we tested for main effects and interactions of site, rotation treatment intensity, and aggregate size class. Multiple comparisons of rotation treatments were calculated using Tukey's HSD. Statistical analyses were done using JMP software v. 8.1. (SAS, Cary, NC, 2015).

Results

Soil-Inherent Wind Erodibility

The largest size class of aggregates comprised the majority of aggregates at the Sterling and Stratton sites (Fig 2.1). The erodible fraction of the soil, aggregates less than 0.84 mm, composed the second-largest class at Sterling and Stratton, making up 24% and 23% of each site's soils respectively. Walsh, with sandier soils and higher potential evapotranspiration, had the majority of aggregates (79%) in the erodible size fraction. Every phase of each cropping system is planted every year at the sites. The May sampling occurred prior to planting of summer crops but while winter wheat was growing. Examining the mean erodible fraction by the crop phase at the time of sampling, there was a significant difference only at Stratton with strips in corn residue displaying the most erodible size fraction of soils and wheat residue the least amount of erodible size soil aggregates (Fig 2.2, Table 2.4). There were no differences in the amount of erodible fraction by crop rotation system at any of the sites (Table 2.3).

Aggregate stability, measured by the energy required to crush soil aggregates, differed by site. Walsh had the lowest and Stratton the highest stability (Figs 2.2 and 2.3; Tables 2.5 and 2.6). Aggregate stability differed by crop phase only at Stratton. Soil aggregates in growing winter wheat stands were more stable than both the corn and forage crop residue plots (Fig. 2.4, Table 2.6). Stratton was also the only site to display differences by crop rotation, with the wheat-fallow treatment being more stable than the continuously cropped treatment (Fig 2.3, Table 2.5).

Carbon Distribution

Organic carbon distribution differed by site and by erodible size fraction (Table 4). Carbon concentration increased with aggregate size class, though there was a site by size class interaction (Fig. 2.5; Table 2.7). Within sites, Walsh had more carbon in the largest size fraction (>6.35mm) relative to the smaller size fractions. The other sites had no significant differences in organic carbon between size fractions but followed similar trends of increasing carbon with size class (Fig.2.5).

We hypothesized that more intense cropping systems would result in higher soil organic carbon. Soil organic carbon did not differ by cropping intensity at any of the sites (Fig 2.6, Table 2.8).

Soil Moisture

During the 14 days prior to soil sampling in the spring of 2015, Walsh received 98mm of precipitation, Sterling 37mm, and Stratton 104mm. At the time of sample collection, soil moisture was greater in growing wheat strips than the other strips with the previous year's crop residue at Stratton ($P < 0.0344$). Soil moisture at sampling was positively correlated with aggregate stability across all sites ($P< 0.002$) and negatively correlated with the amount of soil in the erodible fraction ($P< 0.010$).

Discussion

A soil's inherent wind erosion potential is determined by aggregate size and stability (Merrill et al. 1999). There are several management and environmental factors that influence these soil properties, including management, weather, soil properties, and cropping history (Tatarko 2001). In this study we examined both the long-term impacts of cropping history and the short-term impact of the most recent crop on the wind erosion potential of soils from a long-term dryland cropping system experiment at three locations in eastern Colorado.

Both crop rotation system and current crop phase influenced soil properties, but only at a single location. We found that crop rotation system had no significant influence on the amount of erodible fraction or organic carbon at any of the sites. As expected, Walsh with the lowest clay content that could facilitate aggregation, had the highest erodible fraction. Crop rotation system affected aggregate stability at Stratton, but not the other sites. The current phase of the crop system also played a significant role in the erodible fraction and aggregate stability at Stratton. Half of the wheat-fallow strips and one-third of the wheat-corn-fallow strips at all sites would had been in fallow the previous growing season and had growing wheat at the time of sampling. The higher residue present throughout the wheat-fallow rotation may have insulated the aggregates on those plots from the destructive forces of freeze-thaw cycles and freeze-drying. Soil moisture was also higher in these strips with growing wheat relative to non-wheat strips, but again only at the Stratton location, which received the greatest amount of precipitation among the sites in the 14 days prior to sampling.

The within-site differences in aggregate size and stability displayed at Stratton could be facilitated by the site's high clay content. While soil structure is dependent on the interaction of many factors clay content is an influential factor (Kay 1990; Bronick and Lal 2004). Clay content up to 25% and gravimetric water content at -1500 J kg^{-1} matric potential were both found to be good predictors of mean aggregate stability (Skidmore and Layton 1992). The small particle size, high surface, area and cation exchange capacity of clay particles allow them to adhere to binding agents in organic matter, root exudates, and microbially-produced polysaccharides. Another study found that higher clay soils had increased aggregation with equal additions of crop residue (Wagner et al. 2007). A recent study of dryland no-till sites in eastern Colorado and south-western Nebraska including Walsh, Sterling, and Stratton, found an interaction of clay with soil biology and carbon influencing aggregation (Rosenzweig et al. 2018).

The lack of a cropping system legacy impact on aggregate size and stability at two of the three locations may also have been due to temporal dynamics of the larger soil aggregates. Dry soil aggregate size and stability may be more affected by short- and intermediate-term factors such as weather, soil moisture, root structure, and new residue inputs than by cropping intensity legacy. Changing overwinter weather conditions including freeze-thaw and freeze-drying cycles can decrease aggregation (Tatarko 2001; Layton et al., 1994). Blanco-Canqui et al. (2013) found the effects of intensification using cover crops on dry soil properties did not persist 9 months following termination of the cover crop. Macroaggregates formed by the binding of root structures and fresh residues may be most susceptible to the effects of annual weather and crop growth cycles, re-aggregating and fracturing on relatively short time scales.

Previous studies at these sites have found greater organic carbon in more intensely cropped systems (Sherrod et al., 2003). Our study did not confirm these results, possibly because this study focused entirely on the summit slope positions, whereas the toeslopes have higher effective precipitation, higher overall productivity and residue inputs, and thus have higher organic carbon (Cantero-Martinez et al. 2006). The Great Plains region also experienced a high frequency of drought conditions from 2010-2015, reducing the production of biomass and microbial activity (Nielsen et al., 2016).

Ecological models depend on validation with field data. The Wind Erosion Prediction System (WEPS) helps producers and conservation workers to understand the impacts of management decisions on this aspect of soil degradation. Submodels in WEPS estimate properties such as aggregate stability and size distribution to calculate both the amount of soil available to be eroded and the potential for the soil aggregates to be damaged by abrasion. The addition of this study's field data from long-term research sites can help to add to the library of data used to validate the model.

Addressing the issue of wind erosion is of vital importance to maintain the productive capacity of agricultural soils in arid and semi-arid regions. Our study suggests that the main management-driven impacts on soil erodibility may include both short-term crop effects on moisture and residue inputs and longer-term cropping system influences, but that soil texture and moisture are key mediating variables. Links between cropping intensity, soil carbon, and wet aggregate stability found in previous studies may not hold for the larger aggregates that contribute to dry aggregate stability. The turnover rate of macroaggregates formed under the influence of recent crops should not be overlooked when considering soil-inherent wind erodibility.

Table 2.1. Historical precipitation, growing season open pan evaporation (March to October), soil type at the summit slope position, and annual precipitation during the study from the Dryland Agroecosystem Project (DAP) sites near Walsh, Sterling, and Stratton, Colorado. Adapted from Peterson, et al, 2001 and Cantero-Martinez et al. 2006

Site	**Location**	**Elevation Ft (m)**	**Historical Average Annual Precipitation (mm)**[a]	**Open Pan Evaporation (mm) (March-October)**	**Annual precipitation during study (mm)**[a]	**Soil Type**	**Surface 10 cm Soil Texture**	**Soil Classification**
Walsh	37.23° N 102.17° W	3720 (1134)	395	1975	226(2014) 504(2015) 399(2016)	Sandy Loam	Clay: 17% Silt: 18% Sand: 65%	Fine-Loamy, mixed mesic Aridic Ustochrept
Sterling	40.37° N 103.13°W	4400 (1341)	440	1600	433(2014) 510(2015) 364(2016)	Loam	Clay: 21% Silt: 34% Sand: 45%	Fine-silty, mixed, mesic Aridic Argiustoll
Stratton	39.18° N 102.26°W	4380 (1335)	415	1725	357(2014) 331(2015) 286(2016)	Clay Loam	Clay: 34% Silt: 41% Sand: 25%	Fine-silty, mixed, mesic Aridic Argiustoll

[a] Precipitation data from CoAgMet (http://www.coagmet.colostate.edu/index.php). The 2014-2016 data from CoAgMet. Some Stratton data taken from nearby Kirk site due to missing data from Stratton CoAgMet station during study period

Table 2.2. Descriptions of cropping systems and abbreviations used.

Cropping System Abbreviation	**Cropping System**	**Description**
W-F	Wheat-Fallow	Winter wheat planted October, harvested the following July. Fallow the 14 months following harvest to the next wheat planting
W-C-F	Wheat -Corn-Fallow	Winter wheat planted October, harvested the following July. Corn planted the following May. Corn harvested in October, then fallow 12 months until winter wheat planted. In this system grain sorghum is substituted for corn at Walsh.
CC	Continuously cropped opportunity-maximization or biomass production systems	The sites include two different continuously cropped rotation systems. One relies exclusively on summer annual forage or hay crops, which are usually planted June and harvested September of the same year. Crops have included forage sorghum, hay millet, and forage soybeans. The second system is primarily continuous grain-based that includes wheat, corn, grain sorghum, and occasionally other crops such as cowpeas. The objective of these systems is either to maximize biomass production by focusing on forage crops or maximize the opportunity of expected weather or market potential with the choice of grain crops.

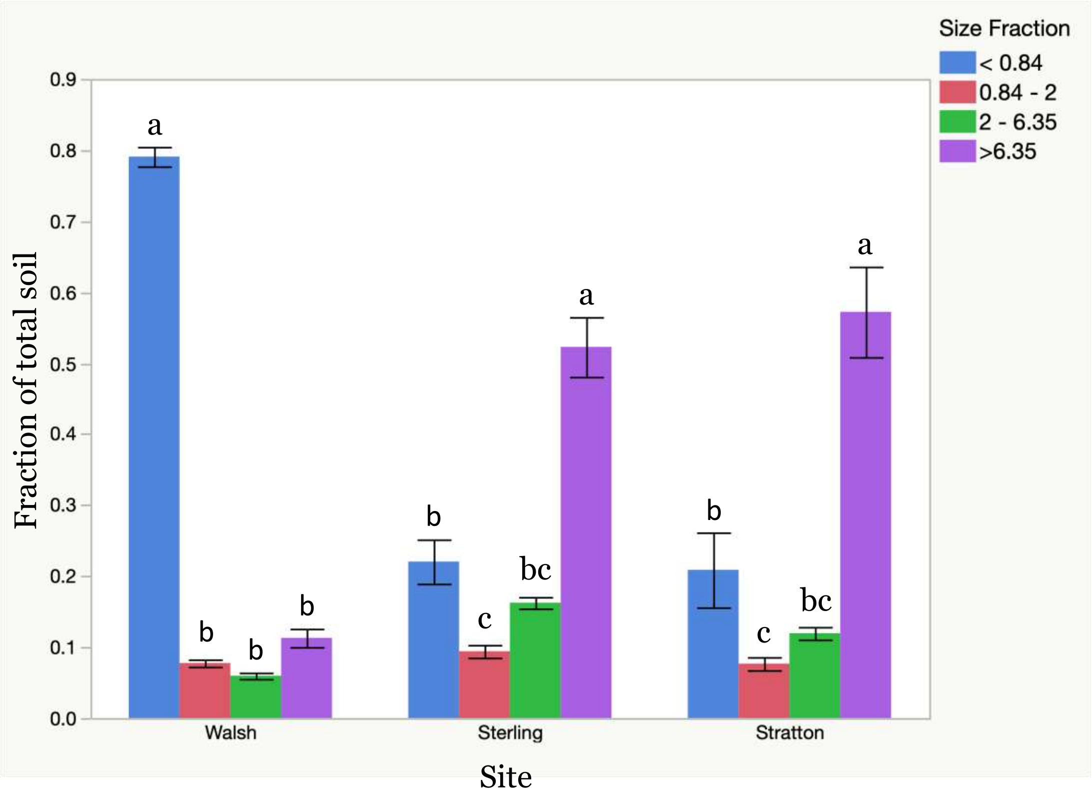

Figure 2.1. Aggregate size distribution by site as a percent of total soil sample by mass. Sample taken to 5 cm depth. Aggregate size fractions are in mm. Letters indicate significantly different means within a site at $P < 0.05$ using Tukey HSD

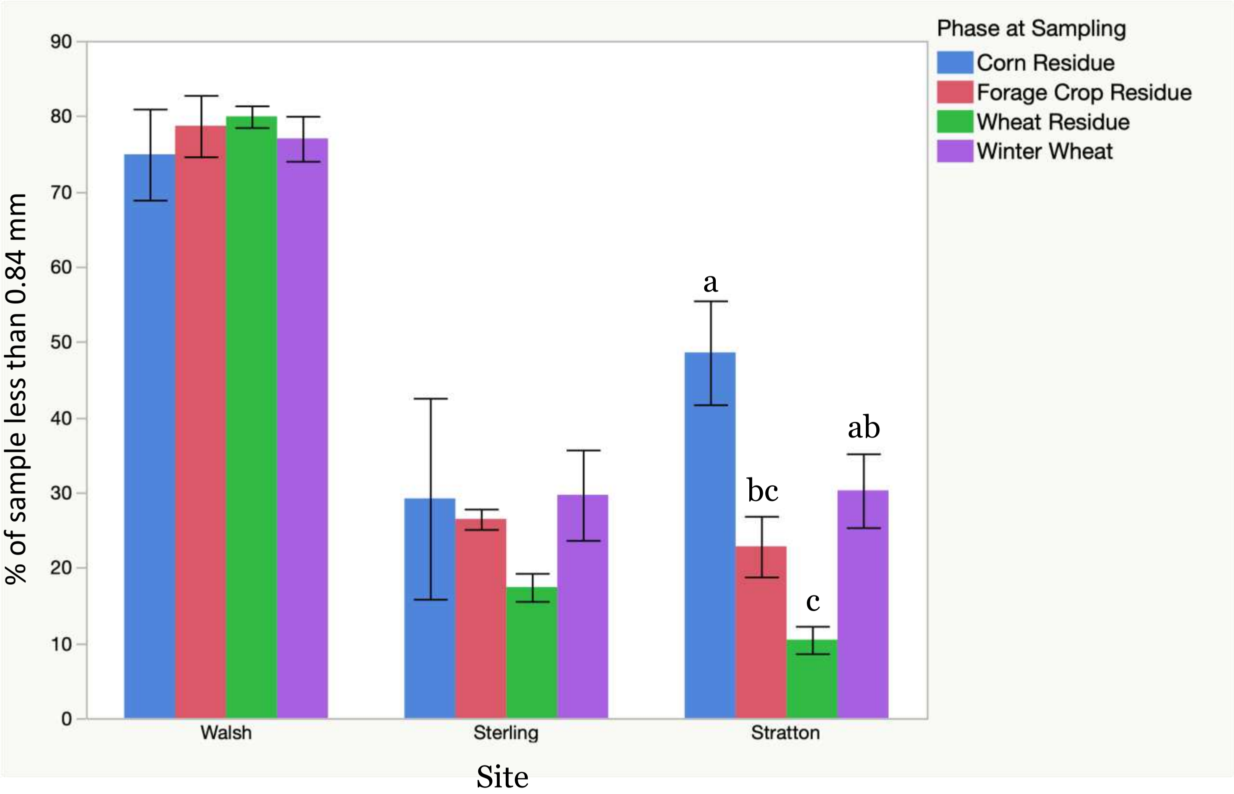

Figure 2.2. Erodible fraction of soil by crop phase at sampling. Samples taken to 5 cm depth. Letters indicate significantly different means within a site at P < 0.05 using Tukey HSD

Table 2.3: Analysis of Variance for mean erodible fraction of total soil. Samples taken to 5 cm depth.

Analysis of Variance	***P >F***
Site	**<0.0001**
Crop Phase at Sampling	**0.0003**
Site* Crop Phase at Sampling	**0.0005**

Table 2.4. Mean erodible fraction and Geometric Mean Diameter (GMD) of total soil in the surface 5 cm of each cropping system.

Site	**Cropping System**	**Mean Erodible Fraction (%)**	**Mean GMD (mm)**
Walsh	W-F	81.68	0.11
	W-C-F	76.00	0.17
	CC	78.52	0.15
Sterling	W-F	19.67	4.93
	W-C-F	28.01	4.04
	CC	23.46	3.98
Stratton	W-F	20.71	4.74
	W-C-F	29.97	3.83
	CC	18.26	7.71

Analysis of Variance		***P >F***	***P >F***
Site		**$P < 0.0001$**	**$P < 0.0003$**
Cropping System Intensity		$P = 0.3826$	$P = 0.5437$
Site* Cropping System Intensity		$P = 0.3670$	$P = 0.5520$

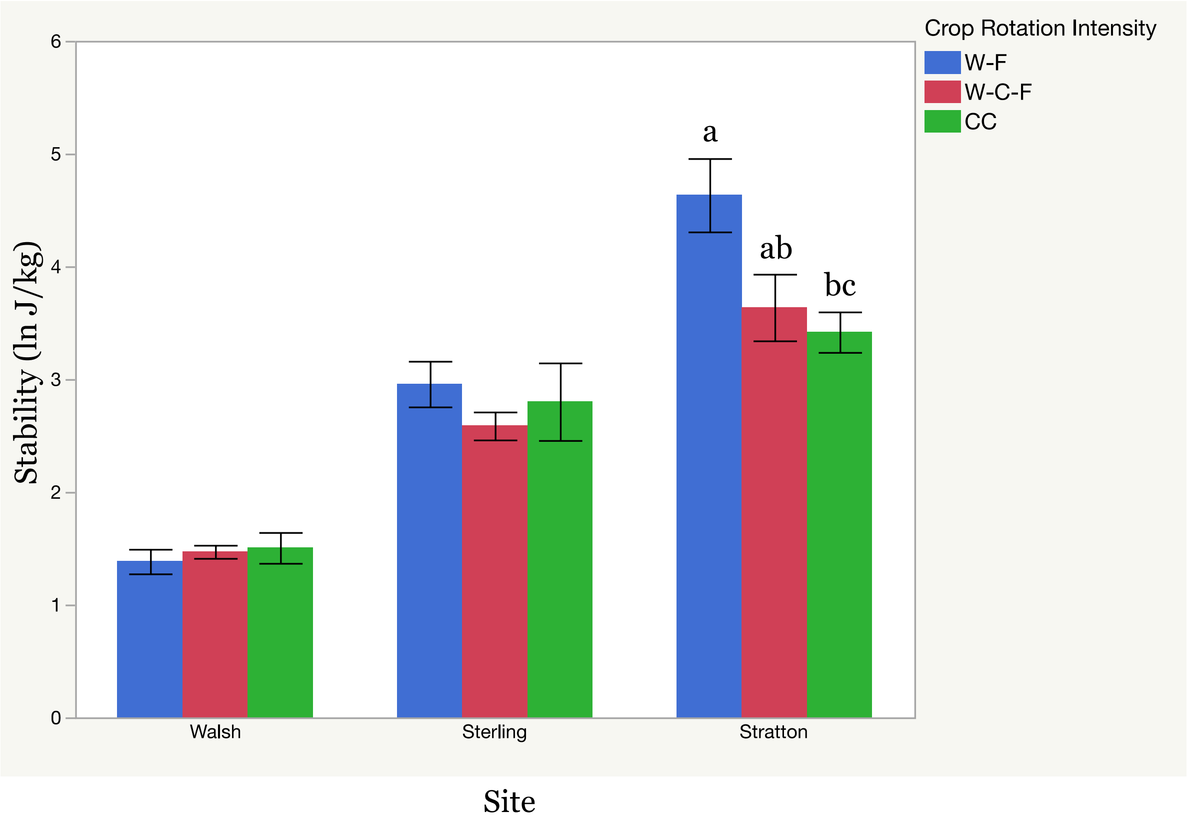

Figure 2.3. Aggregate stability (ln J kg^{-1}) for each of three cropping system intensities at each of three study sites. Letters indicate significantly different means within a site at P < 0.05 using Tukey HSD.

Table 2.5. Dry aggregate stability for each cropping intensity at each site. Samples taken to 5 cm depth.

Analysis of Variance	***P >F***
Site	**<0.0001**
Cropping System Intensity	0.0577
Site* Cropping System Intensity	0.0597

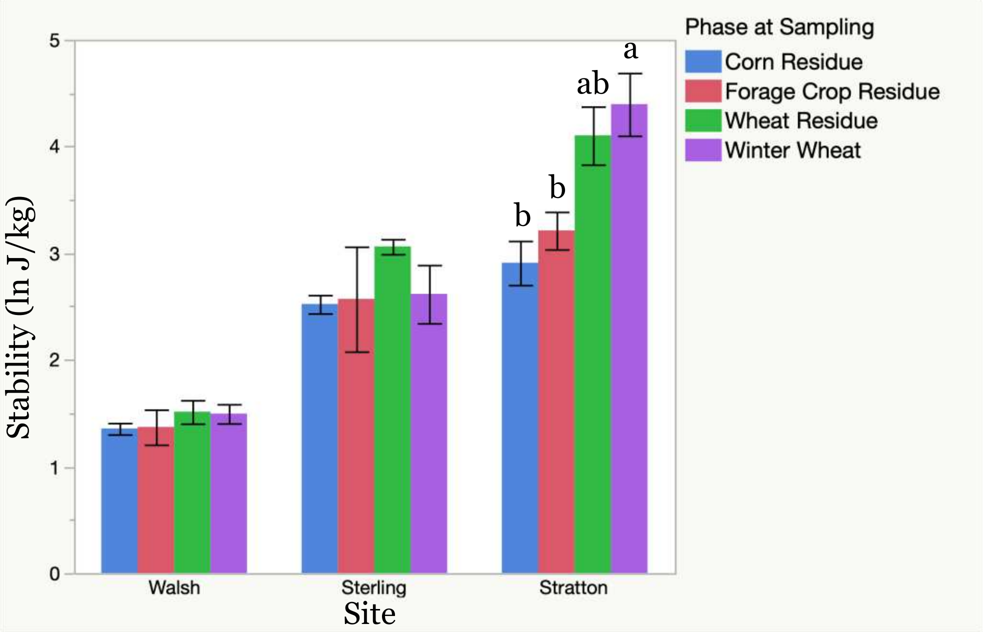

Figure 2.4: Aggregate stability (ln J kg^{-1}) by crop phase at time of soil sampling for each of three study sites. Letters indicate significantly different means within a site at $P < 0.05$ using Tukey HSD.

Table 2.6. Analysis of Variance for dry aggregate stability of soil in the surface 5 cm.

Analysis of Variance	***P >F***
Site	**<0.0001**
Crop Phase at Sampling	**0.0093**
Site* Crop Phase at Sampling	0.1083

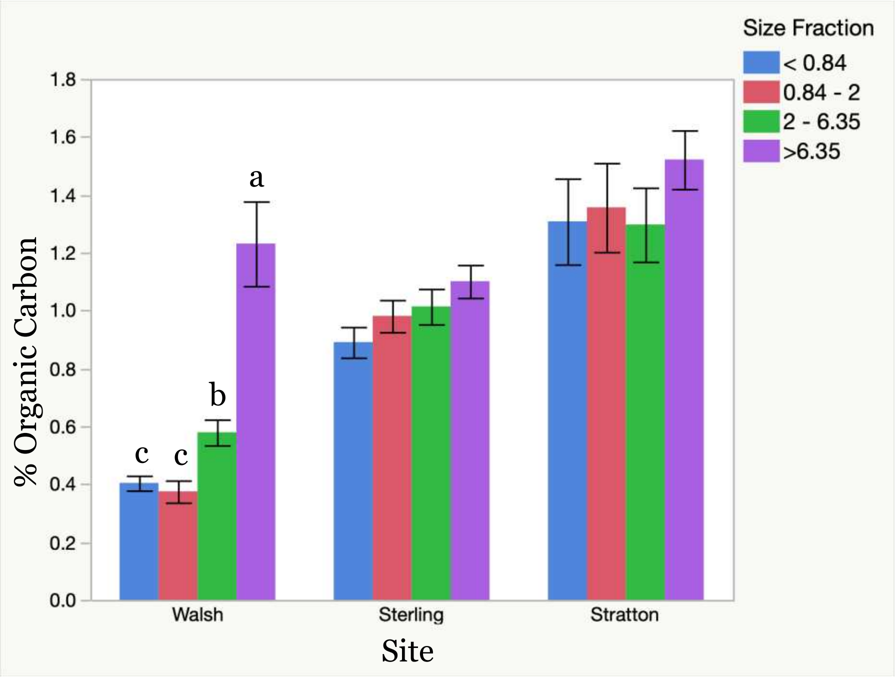

Figure 2.5. Percent of each aggregate size fraction comprised of organic carbon in the surface 5 cm at each of three study sites. Letters indicate significantly different means at $P < 0.05$ using Tukey HSD.

Table 2.7. Percent Soil Organic Carbon Concentration by size Fraction

Site	**Cropping System Intensity**	**< 0.84 mm**	**0.84 – 2 mm**	**2 – 6.35 mm**	**> 6.35 mm**
Walsh	W-F	0.363 (0.05)	0.277 (0.06)	0.482 (0.03)	0.785 (0.0)
	W-C-F	0.399 (0.11)	0.426 (0.19)	0.602 (0.22)	1.412 (0.25)
	CC	0.452 (0.10)	0.396 (0.09)	0.642 (0.14)	1.134 (0.0)
Sterling	W-F	0.901 (0.18)	0.984 (0.21)	1.315 (0.24)	1.157 (0.21)
	W-C-F	0.887 (0.11)	0.9666 (0.16)	1.050 (0.22)	1.000 (0.17)
	CC	0.879 (0.41)	1.016(0.31)	0.931 (0.15)	1.241 (0.11)
Stratton	W-F	1.302(0.61)	1.440(0.56)	1.315 (0.48)	1.366 (0.32)
	W-C-F	1.69(0.38)	1.068(0.29)	1.147 (0.23)	1.649 (0.33)
	CC	1.599 (0.42)	1.908 (0.50)	1.976 (0.0)	1.505 (0.0)

Analysis of Variance	**P>F**
Site	**<0.0001**
Cropping System Intensity	0.1472
Aggregate size class	**<0.0001**
Site* Aggregate size	**0.0076**

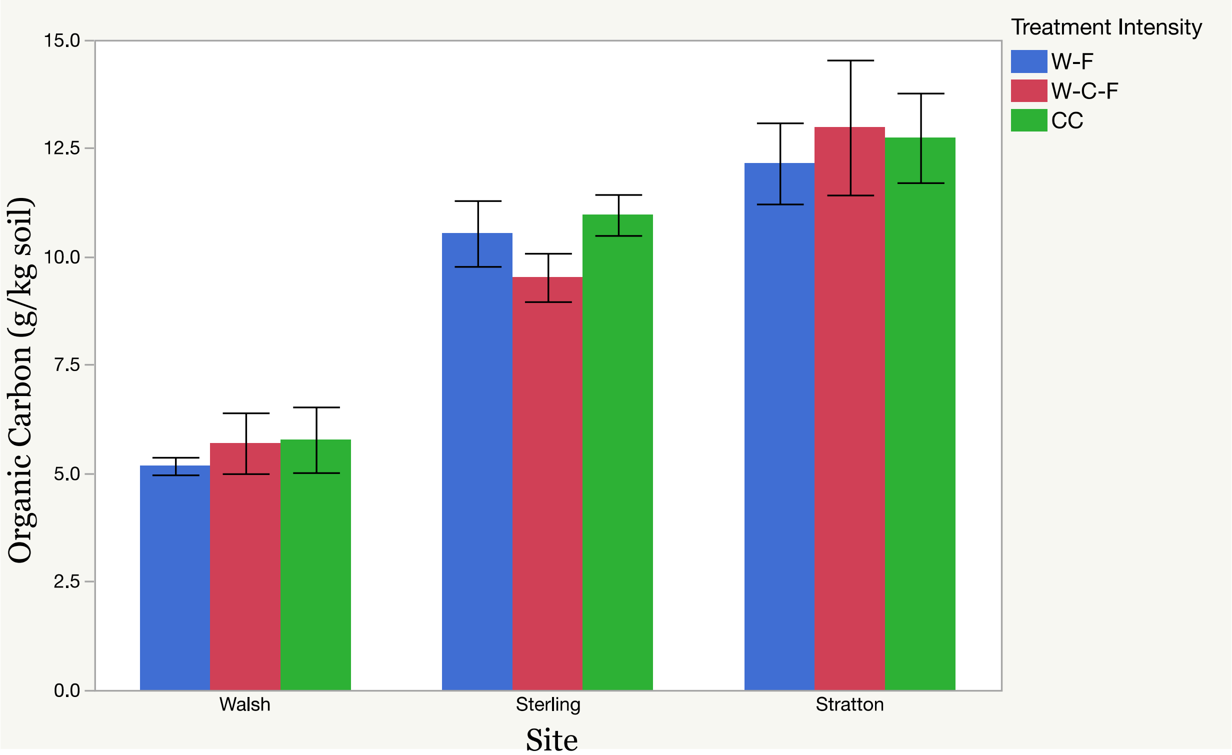

Figure 2.6. Soil organic carbon to 5 cm affected by site and cropping intensities. Letters indicate significantly different means at P < 0.05 using Tukey HSD.

Table 2.8. Analysis of Variance for Soil Organic Carbon (g C kg $soil^{-1}$) *P>F*

Factor	***P >F***
Site	**<0.0001**
Cropping System Intensity	0.7503
Cropping System Intensity*Site	0.8242

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Conclusion

Wind erosion is a soil degradation issue affecting arid and semi-arid regions around the globe. The effort to minimize wind erosion losses depends on continued advances improving both the accuracy of models and exploring the interwoven factors of climate, soil, management, and crops. Conservation efforts prioritized in part by vulnerabilities identified through modeling have led to strong reductions in soil loss in the US.

While modeling has been refined over the decades, there remains a need for field validation in a variety of settings. Studies such as these which examine all of the modes of wind erosion prevention at locations with a long-term known management history add depth to the broad field of knowledge. The Dryland Agroecosystem Project (DAP) provides a range of no-till cropping system intensities within the context of a semi-arid environment. The DAP provided an opportunity to study both the long-term influences of cropping systems on soil-inherent wind erodibility and the shorter-term influences of crop residue cover and cropping phase.

The adoption of no-till practices has resulted in benefits to the producer and to the soil. Producers see lower labor costs and improvements in water use efficiency and soil structure. Less mechanical damage to soil aggregates and larger amounts of standing and flat residues after harvest decreases the susceptibility to wind erosion. No-till agriculture, though, is not the sole management consideration. Choices in cropping system intensity and of the crops themselves have implications for both short- and long-term soil properties.

The three fundamentals of wind erosion prevention are reducing wind speed, protecting the soil surface from wind contact, and strengthening soil aggregates. These studies sought to explore the interaction of crop rotation intensity, residue production, and wind erodibility at these sites. There were two sections, each with a question as a theme:
1: Do residues of different crop types influence temporal soil cover patterns?
2: Does crop rotation system impart long-term impacts on soil aggregation properties?

The investigation of the first question addressed reducing wind speed and reducing wind contact with the soil surface by examining the temporal dynamics of residue cover. The investigation of the second question addressed the fostering of aggregation properties by crop residues and cropping system legacy through carbon inputs, clay and water contents as well as the mitigating effects of residues against freeze-thaw and freeze-drying.

I hypothesized that residue cover would fit an exponential decay model and that soil cover would be higher and persist longer for winter wheat than summer annual crops. The results did not support an exponential decay model for wheat residue cover but did show wheat residue persisting longer as protective soil cover than forage residues.
The second hypothesis that a history of continuous cropping would result in higher soil carbon, greater aggregation, and reduced erosion susceptibility relative to wheat-fallow rotation was only partially supported by the data; with only one site showing significant differences between aggregate stability by cropping system.

Addressing the issue of wind erosion is of vital importance to maintain the productive capacity of agricultural soils in arid and semi-arid regions. Isolated movements towards conservation involving only one management practice can have limited impact on areas of environmental and financial concern to both producers and the general public. The layering of conservation efforts strengthens their impacts. Intensification of cropping systems in semi-arid regions along with reducing tillage can result in enduring soil benefits and greater annualized crop yields. Giving consideration to crop choice can add to the positive consequences. Maintenance of crop residues and management practices which maximize residues and soil cover can help compensate for a low soil-inherent erosion resistance due to either soil texture or climate. Our results reinforce the benefits of winter wheat as the cornerstone crop in this semi-arid region, Wheat produces dense stand counts, post-harvest standing stems, and a large amount of persistent residue can physically protect the soil from wind erosion. With thoughtfulness and effort, another Dust Bowl on the Great Plains can not only be prevented but can truly fade into legend.

Appendix

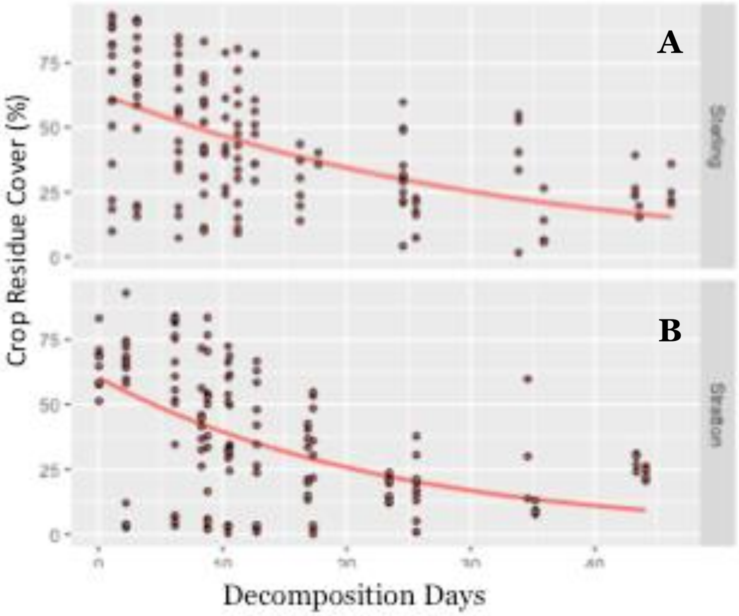

Figure A.1. Exponential decay model for decline of forage residue cover for A) Sterling and B) Stratton sites.

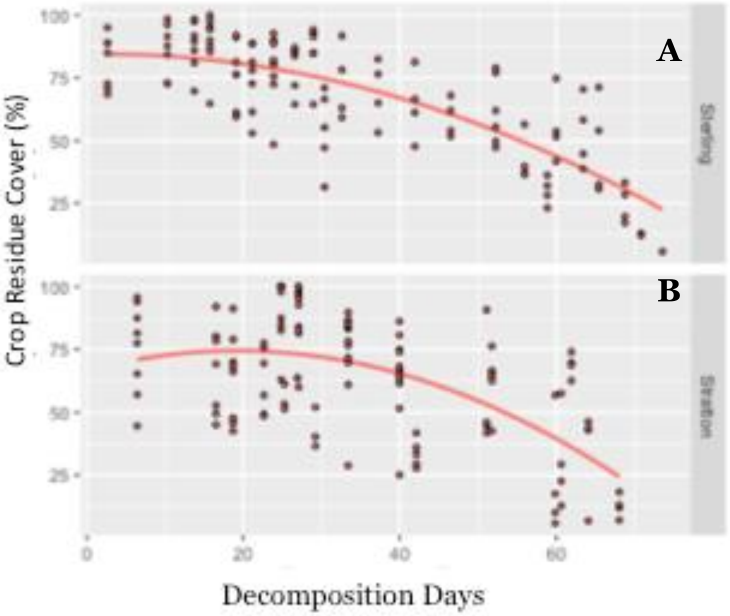

Figure A.2. Quadratic model fit for wheat residue cover decline for A) Sterling and B) Stratton sites.

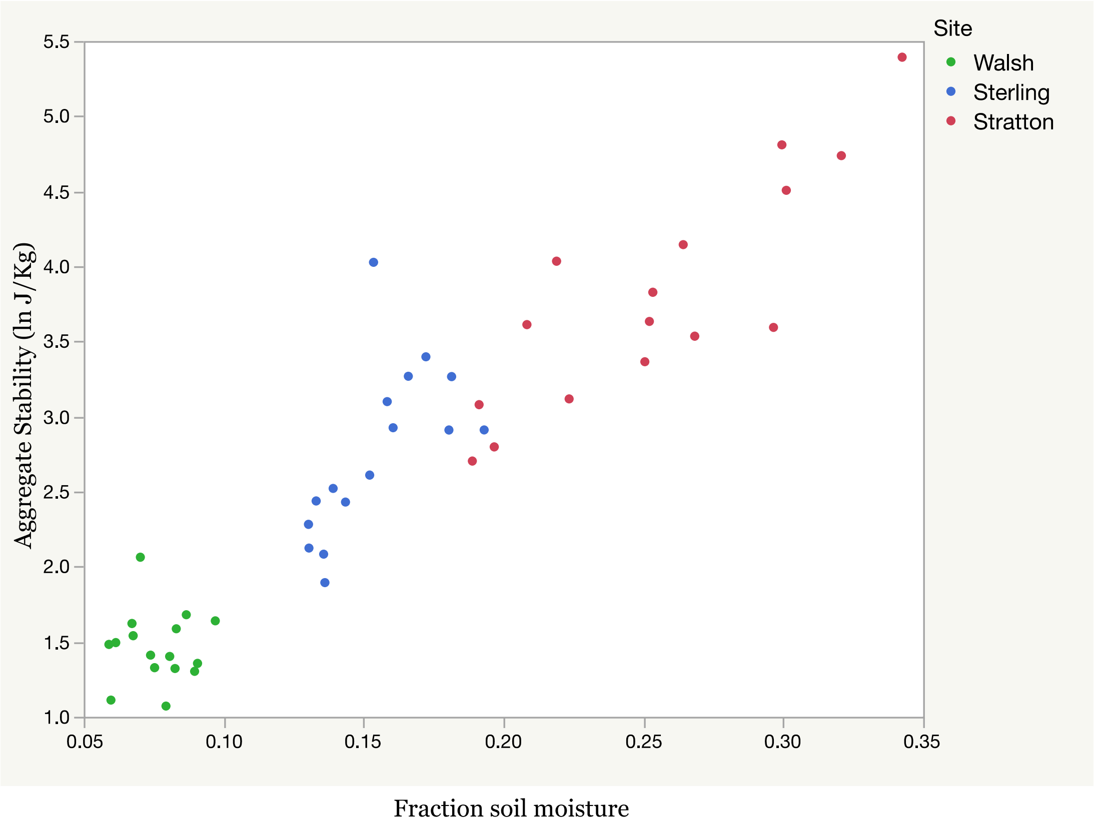

Figure A.4. Soil moisture content by aggregate stability at each of 3 study sites.

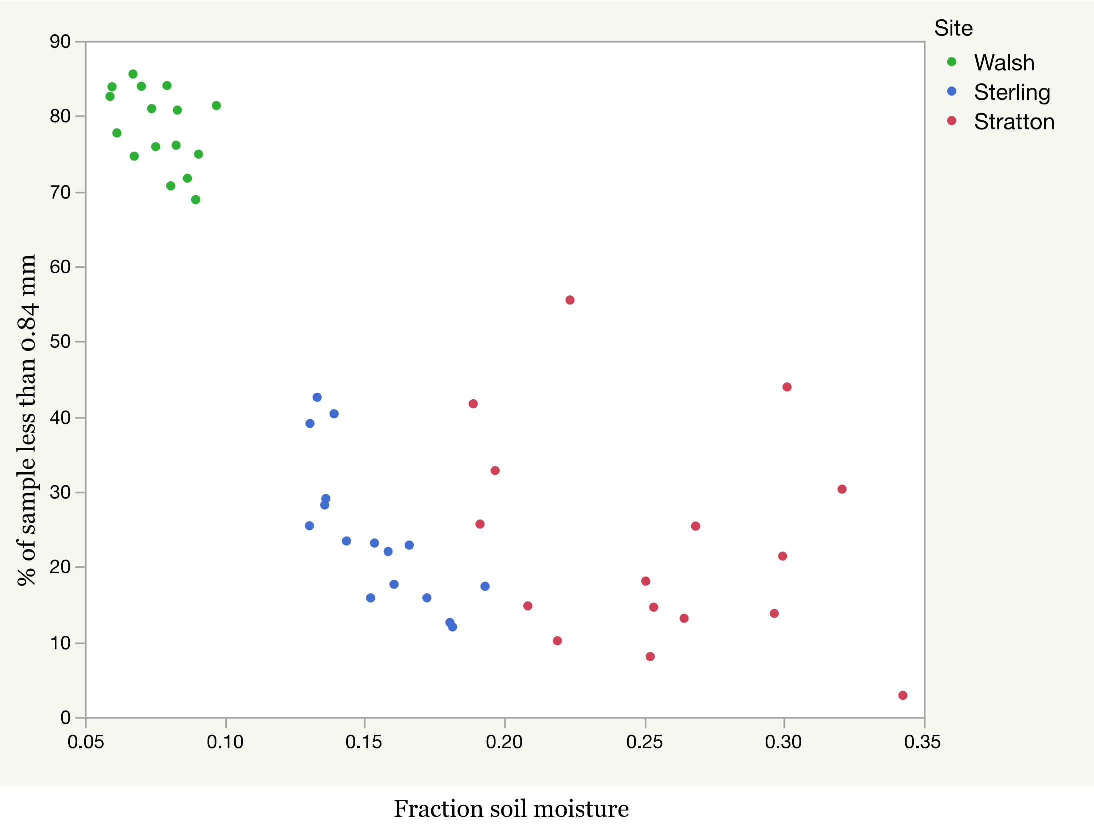

Figure A.5. Soil moisture content by erodible fraction at each of 3 study sites.