A COMPARATIVE STUDY OF SOIL MOISTURE ON CULTIVATED AND CONSERVATION RESERVE PROGRAM LAND IN DOUGLAS COUNTY, WASHINGTON

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ABSTRACT

A COMPARATIVE STUDY OF SOIL MOISTURE ON CULTIVATED AND CONSERVATION RESERVE PROGRAM LAND IN DOUGLAS COUNTY, WASHINGTON

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As populations grow, efficient soil moisture management in dryland farming environments will be essential to maintaining global food security. This study examined farmland soil moisture in relation to land use (conventional tillage, no tillage, and CRP) considering the factors of precipitation, evaporation, and air temperature from April 3, 2011 – September 16, 2011 in eastern Douglas County, WA. Conventional tillage fallow dust mulch was effective in reducing the effects of evapotranspiration and air temperature, while active wheat fields, CRP, and no tillage fallow all had reduced soil moisture when evapotranspiration and air temperature increased. This indicated that crops, natural vegetation, and weeds all impact soil moisture through transpiration. Overall, no significant difference in soil moisture was found between tillage methods; therefore, no tillage is recommended for environmental benefits and decreased on-the-farm costs.

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CHAPTER I

INTRODUCTION

Problem

Drylands are regions where water is scarce, soil water is low, and the growing season ranges from 1–179 days (Koohafkan & Stewart, 2008; Laity, 2008). Dryland climates are typified by a variable temperature range, high evaporation, and low precipitation of up to 700 mm annually (FAO, 2000; Koohafkan & Stewart, 2008). Drylands cover approximately 45% of the world's total land area, and are classified as regions with arid, semi-arid, and dry sub-humid climate conditions (FAO, 2000; Stewart & Koohafkan, 2006). Arid regions, or deserts, have higher potential evaporation than precipitation, and a wet period of 1 to 3 months. Semi-arid regions receive more precipitation than arid regions, but experience low soil moisture and limited crop production with a 3 to 4 month wet period (Ryan, 2003). In dry sub-humid regions, annual rainfall exceeds annual evapotranspiration, with a majority of precipitation occurring during a four to six month wet season (Brouwer & Heibloem, 1986).

Location has a significant impact on where drylands occur across the globe (Figure 1.1). Drylands are found in four broad regions: beneath subtropical highs at the mid-latitudes (~30º), in continental interiors, leeward of mountain ranges, and adjacent to cold ocean currents. Arid and semi-arid drylands occur most commonly in the lower mid-latitudes between 30° and 35° in both the northern and southern hemispheres, while dry sub-humid climates appear mostly in continental interiors (Laity, 2008). The mid-latitudes are areas of atmospheric subsidence and anti-cyclonic weather. Hot, moist air near the equator rises and travels to the mid-latitudes where it warms and dries as it descends toward the earth (Laity, 2008; Turkes, 1999). Orographic lifting occurs when air from low elevations moves to higher elevations along a mountain slope. As the air rises, it expands, cools, and eventually condenses, which results in cloud formation and precipitation as it moves toward the summit (Andrews, 1996). Cold air descends as it passes to the leeward side of the mountain (Ferguson, 1999). These areas are dry due to atmospheric subsidence, where the cooling air becomes progressively warmer and drier as it descends (Andrews, 1996; Ferguson, 1999; Laity, 2008). This rain shadow effect results in clear skies, higher solar radiation, and low humidity on the leeward side of mountains (Shmida, 1985; Wainwright, Mulligan, & Thornes, 1999).

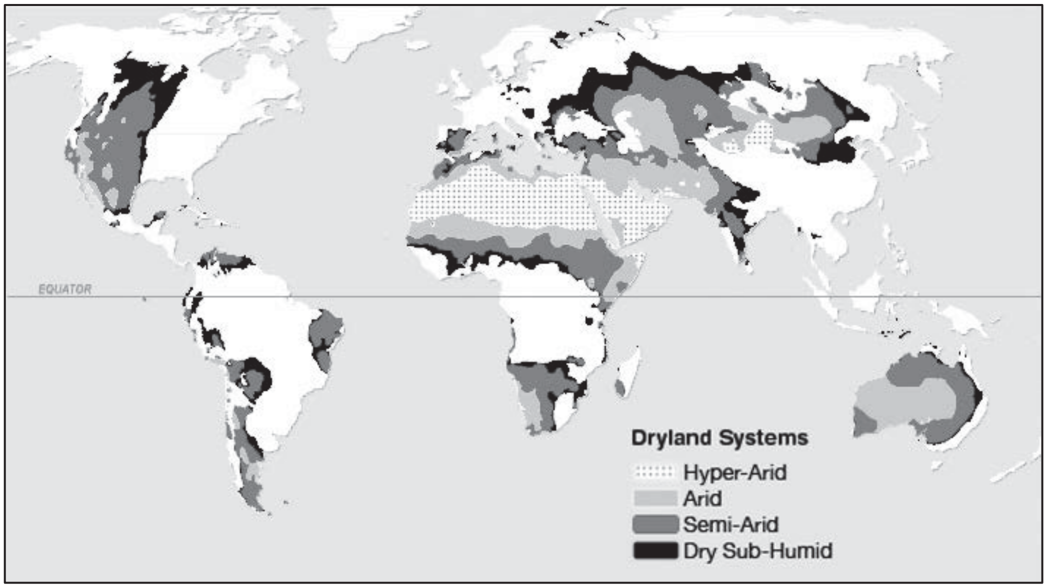

Figure 1.1. Worldwide distribution of drylands (Millenium Ecosystem Assessment, 2005).

The arid and semi-arid regions of North America are primarily formed by the rain shadow effects of mountain ranges such as the Cascades, Rockies, Sierra Nevada, and Sierra Madres (Shmida, 1985). Located in the mid-latitudes, and in the rain shadow of the Cascade Mountain Range, the semi-arid drylands in eastern Washington State receive an average of <300mm – 600 mm precipitation annually (Schillinger & Papendick, 1997).

On the central portion of the Columbia Plateau, Washington's eastern Douglas County receives approximately 250 mm of precipitation annually. This provides the sole source of moisture for non-irrigated crops (Macinko, 1985).

Soil moisture is the main factor influencing plant growth in dryland ecosystems (Coronato & Bertiller, 1996). Many factors influence the amount of moisture in the soil, including precipitation, evaporation, topography, soil texture, and tillage **(**Brady & Weil, 2000; Buol, Hole, & McCracken, 1989)**.** Water is essential for growth and production of crops; therefore, efficient capture and retention of precipitation of the soil in dryland farming environments is the key to success (McCall & Wanser, 1924; Turner, 2004). Dryland agricultural systems have been adapted to maximize soil moisture capture and retention of precipitation, and reduce evaporation while providing stable crop production (Amir, Krikun, Orion, Putter, & Klitman, 1991; Fischer & Turner, 1978; Oram, 1980).

In dryland areas, crops may obtain water in two ways: irrigation and rain-fed (i.e., dryland). Irrigation artificially brings water to crops and can be utilized in areas where a water source is readily available (Unger, Payne, & Peterson, 2006). Rain-fed farming is done without the aid of irrigation, relying solely on precipitation to water crops (Hargreaves, 1957). While irrigated crops can receive water as needed, rain-fed crops depend completely on moisture captured and stored in the soil between precipitation events. Efficient soil water capture and retention is vital to the success of crop production in rain-fed farming (Unger et al., 2006).

Rain-fed crops in dryland environments grow under moderate to severe moisture stress (Oram, 1980). Cereal crops, such as wheat, are well-suited to grow in low rainfall areas (Juergens, Young, Schillinger, & Hinman, 2004; Koohafkan & Stewart, 2008). It is estimated that one-quarter of the world's cereal production is farmed using rain-fed agriculture (Australian Centre for International Agricultural Research, 2002). Wheat, barley, oat, rye, rice, maize, sorghum, and millet account for 50 percent of the protein and 56 percent of the food energy consumed on Earth (Stoskopf, 1985). Dryland grain production is expected to increase in the future due to the needs of a growing world population that will require more food and water. The Food and Agricultural Organization (FAO) estimates an increase in need for cereal grains from 1.9 billion tons in 2001 to 3 billion tons in 2050 (FAO, 2006). Relying on irrigation to keep pace with this demand is unsustainable because of limited water supplies. In some dryland areas, fossil water, which exists in non-renewable aquifers, is being used to irrigate crops. Even in areas where groundwater is recharged, it is frequently used to irrigate crops at a rate that exceeds recharging (Koofhafkan & Stewart, 2008). Improved efficiency in use of available water in these dry environments is critical (Australian Centre for International Agricultural Research, 2002; Koofhafkan & Stewart, 2008).

The main goal of rain-fed farmers worldwide is to efficiently utilize any available precipitation and reduce runoff (Koohafkan & Stewart, 2008). High-intensity storms are common in dryland areas, and water losses through runoff can be significant. Worldwide water harvesting methods such as terraces, contour furrows, catchments, and fallowing are utilized to increase moisture storage and decrease runoff in rain-fed environments (Koohafkan & Stewart, 2008; Stewart, 2009).

In the dryland areas of the Pacific Northwest, the winter wheat/summer fallow system is the dominant rainfed method of improving soil moisture. The summer fallow system retains soil moisture by producing one crop every other year on a given piece of land, and leaving the land unplanted, or fallow, during alternate years (Schillinger, Schofstoll & Alldredge, 2008). While the land lays fallow, the moisture that would otherwise be used by crops accumulates beneath the surface (McCall & Wanser, 1924). The additional soil moisture gained through the fallow year increases soil moisture at the time of seeding. This practice makes farming viable in areas where one year of precipitation would not be adequate to produce a crop (Unger et al., 2006).

In addition to the summer fallow system, soil water capture and retention can also be affected by particular tillage practices. The degree to which the land is tilled affects the soil's organic matter, erosion potential, temperature, and density, all of which impact soil moisture (Griffith, Mannering, & Box, 1986). Tillage breaks up the soil surface, allowing precipitation to infiltrate, but can increase evaporation of soil water by exposing moist soil to the atmosphere. Additionally, tillage practices that leave soil residues and mulches can also have an effect on soil moisture gains and losses by increasing infiltration and reducing evaporation (Juergens et al., 2004).

Tillage methods in dryland settings vary worldwide depending on the availability of equipment, crops grown, and the cultural practices of the area (Koohafkan & Stewart, 2008). Tillage methods range from using pack animals and hand tillage methods, to farming under conventional tillage and practicing conservation tillage methods (Cresswell & Martin, 1998).

In the Pacific Northwest, winter wheat is primarily grown under two tillage methods: conventional tillage (CT) and no tillage (NT). With CT, regular passes are made over fallow crop fields with a variety of implements that break up the soil. This practice incorporates organic matter into the soil and prepares the seed bed for planting. The result is a surface “dust mulch” composed of fine, loose soil designed to inhibit evaporation and increase infiltration (Thorne, Young, Pan, Bafus, & Alldredge, 2003). Fallow fields under the NT method experience no cultivation between plantings and therefore retain crop residues, leaving organic matter at the surface. This layer is designed to control water runoff, increase the length of time precipitation has to infiltrate, and reduce evaporation. The primary differences between these methods are the degree of soil disturbance and the amount of surface residues.

In an attempt to improve the quality of highly erodible farmlands, some areas are taken entirely out of production for conservation purposes. The Conservation Reserve Program (CRP) compensates farmers who leave these areas, often adjacent to active crop fields, untouched. By not subjecting these lands to tillage or crop production, native vegetation keeps soil structure intact, reduces erosion, slows runoff, and facilitates water infiltration. CRP aims to improve the health of the entire landscape around the contracted areas (Batie, 1985; Dunn, Stearns, Gutenspergen, & Sharpe, 1993; Karlen, Gardner, & Rosek, 1998).

Purpose

The overall purpose of this study was to examine farmland soil moisture in relation to land use from April 3, 2011 to September 16, 2011 in eastern Douglas County, near

Mold, Washington. Specifically, I measured the seasonal variation of soil moisture under conventional tillage, no tillage, and Conservation Reserve Program land uses while also considering the factors of precipitation, air temperature, evaporation, with consistent topography and soil texture.

Significance

This is the first study to examine the relationship between soil moisture and land use in eastern Douglas County. While many studies have examined soil moisture in dryland farming areas within Washington State (Juergens et al., 2004; Kok, Papendick, & Saxton, 2009; Lindstrom, Koehler, & Papendick, 1974; Papendick, Lindstrom, & Cochran, 1973; Schillinger & Papendick, 1997; Schillinger & Wilkins, 1997 Schillinger, 2001; Schillinger, Kennedy, & Young, 2007), these studies were performed in areas with different soil characteristics and climate, and significantly higher wheat productivity than in eastern Douglas County. This area receives less precipitation, and glaciers formed the landscape, leaving a hummocky terrain, haystack rocks, and rocky soils. This study will provide insight and information regarding land-use choices in this region and may be useful in other areas with similar soil and climate characteristics.

Rain-fed farming comprises a significant portion of the economy in Douglas County and accounts for 85% of all harvested cropland. According to the 2007 census, of the harvested 183,242 acres, 156,046 acres were rain-fed. The remaining 27,196 acres were irrigated. Additionally, 197,553 acres were enrolled in either the CRP, Wetlands Reserve Program, Farmable Wetlands, or Conservation Reserve Enhancement Program (USDA National Agricultural Statistics Service, 2011a).

Choice of tillage regime has an impact on the economics of farming. Study results may provide information that could increase dryland farming efficiency and profitability, which are issues of interest to dryland farmers in Douglas County, other parts of North America, and the world. CT provides more consistent yields, but is more labor intensive and uses far more fossil fuel in its operations than no tillage (Griffith et al., 1986; Juergens et al., 2004). The tillage operations of CT require 4 - 8 passes over the ground compared to the single pass of NT. The high operating costs associated with CT has farmers examining alternative cultivation methods that save fuel and optimize soil moisture while keeping yields high (Juergens et al., 2004). NT has been shown to reduce on-the-farm costs (Gillespie, 2008). Despite an increased need for herbicides with the method, NT requires less fossil fuel and labor (Gillespie, 2008; NRCS, 2011). This finding is confirmed by the NRCS Energy Estimator Tool (2011), which estimates an energy savings of 60% when using NT instead of CT methods on winter wheat/summer fallow in the study area.

An economic comparison between different tillage practices in the dryland agricultural areas of Eastern Washington shows equivalent profitability. Juergens, Young, Schillinger, and Hinman (2004) found, in a five-year study in Ritzville, WA, continuous annual NT spring wheat was economically competitive with CT winter wheat/summer fallow. A five-year study conducted in Lind, WA, by Janosky, Young, and Schillinger (2002) showed no significant difference in grain yield within any year, or in the five-year average between minimum and conventional tillage systems. Further, they found the tillage systems to be economically comparable when considering returns and production costs. In some cases, yields can decrease when switching from NT to CT, but productivity improves within one to three years (Olson, Ebelhar, & Lang, 2004). Little economic risk exists in switching from conventional tillage to a reduced tillage method (Schillinger, 2001).

While choice of tillage directly impacts the costs associated with farming, it also impacts the environment. Tillage practices have different impacts on erosion, runoff of precipitation, and the health of the soil (Cresswell & Martin, 1993). No tillage has been shown to decrease soil erosion, reduce surface runoff, and improve soil structure (Griffith et al., 1986; Kok et al., 2009; Martin, Schrieber, Riepe & Bahr, 1991).

Dryland populations continue growing while supplies of both arable land and water are dwindling. Compounding the problem, many of the large aquifers relied upon for dryland irrigation are depleted beyond recovery (Unger et al., 2006). Rain-fed farming is integral to our efforts to maintain global food security in the future, therefore knowledge of how to effectively farm in marginal non-irrigated environments becomes increasingly important (Koofkahn & Stewart, 2008). It is imperative that precipitation be used as efficiently as possible to keep up with food demand (Unger et al., 2006). It will be crucial to understand how to manage soil moisture efficiently as well as understand land use methods that maximize soil moisture retention.

CHAPTER II

LITERATURE REVIEW

Soil Moisture

Soil moisture refers to the amount of water occupying the pore space and particle faces in soil (Rodriguez-Iturbe & Porporato, 2004). Understanding soil moisture begins with precipitation (the introduction of water into the dryland ecosystem), and soil characteristics that impact infiltration and retention (Phillips & Phillips, 1984). Soil moisture depends on many variables (Rodriguez-Iturbe & Porporato, 2004).

Soil Moisture Types

Three types of soil moisture exist: gravitational water, capillary water and hygroscopic water (Strangeways, 2003). Gravitational water refers to soil water that moves freely through the soil profile by gravity (Wild, 2003). This water is found in the macropore spaces within the soil and is not available to plants because water flows through the soil profile (Brouwer, Goffeau, & Heibloem, 1985; Strangeways, 2003). Capillary water is held in the soil by pulling against gravity through the forces of cohesion and adhesion (Wild, 1993, 2003). Capillary water is found in the micropores of soil and is available for plant use (Brouwer et al., 1985; Wild, 1993, 2003). Hygroscopic water is found in thin films around the soil particles and is not available for plant use (Brady & Weil, 2000; Strangeways, 2003; Wild, 1993, 2003).

Soil holds valuable moisture, which plants utilize during their growth cycle, then transpire into the atmosphere (Strangeways, 2003). Pore space influences the water content in the soil, as does the degree that water clings to the soil, or soil moisture tension (Letey, 1985). Four terms are used when describing soil moisture in relation to plants:

saturation, field capacity, available-water capacity, and permanent wilting point (Brouwer et al., 1985; Wild, 1993, 2003). Saturation is when all of the pore spaces in a soil are filled with gravitational water, which results in low soil moisture tension (Wild, 1993). The upper limit of water-holding capacity in a soil is called the field capacity, while the lower limit is called the wilting point (Letey, 1985). Available-water capacity refers to the soil moisture content between field capacity and permanent wilting point (Wild, 2003). Field capacity happens after a soil is allowed to drain from saturation, where the large soil pores are filled with air and capillary water while the smaller pores are still full of hygroscopic water (Wadleigh, 1955; Wild, 2003). As a soil dries, water that is stored in the soil profile is taken up by the plant roots or evaporated at the surface (Wild, 1993, 2003). The drier the soil becomes, the higher the tension and the more difficult it is for the plant roots to extract moisture (Rodriguez-Iturbe & Porporato, 2004). At permanent wilting point, the soil still contains some hygroscopic water, but it is too difficult for the roots to remove it from the soil. This causes plants to wilt beyond recovery and die (Brouwer et al., 1985; Wild, 1993).

Soil Variables

Soil Composition

Composition relates to the physical components of a soil. The four components are: mineral (~45%), water (~25%), air (~25%), and organics (~5%) (Brady & Weil, 2000). The proportions of these components vary depending on type of soil and climatic conditions (Strangeways, 2003). The mineral component comes from rocks that are broken down into smaller and smaller pieces (Brady & Weil, 2000). A soil’s mineral characteristics depend on the parent rock or mineral from which it originated (Buol, et al., 2003; Wild, 1993).

Water is an essential element in the formation and functioning of soil (Brady & Weil, 2000; Buol et al., 2003; Strangeways, 2003). Soil moisture exists in the air spaces between soil particles and primarily enters the profile from the surface as precipitation (Brouwer et al., 1985; Strangeways, 2003). Due to variation in pore space, soil moisture can vary by volume throughout the soil (Brady & Weil, 2000; Strangeways, 2003). Once moisture enters the soil profile, soil is always vacillating between gains and losses of water (Brady & Weil, 2000). Gains of soil water are determined by the factors of timing and intensity of rainfall events, topography, vegetative cover, surface compaction, and texture and porosity of the soil (Brady & Weil, 2000; Brouwer et al., 1986; Buol et al., 2003). Losses of soil water occur through percolation and drainage, evaporation (including the factors of air temperature, soil temperature, and wind), and transpiration by plants (Evans, Cassel, & Sneed, 1996).

Three types of pore spaces exist in the soil: transmission pores that are large in size and readily drain, storage pores that are smaller in size and retain water against gravity, and residual pores that are the smallest in size and remain filled with water even when the soil is dry (Brouwer et al., 1985; Wild, 2003). When all the pore spaces are filled with water, a soil has reached its saturation point, where the total range of volumetric water content is between 40% and 60% (Wild, 2003). Water falling on soil that has reached saturation, or is impenetrably frozen or compacted, will run off the surface (Burr, 1914).

Organics are the non-mineral matter in soil derived from the decomposition of plants and animals (Wild, 1993). Soil organic matter improves soil quality and plant health by adding vital nutrients to the soil and making them available to plants (Rodriguez-Iturbe & Porporato, 2004). Organic matter in the soil provides structure to smaller soil particles, helping bind the mineral component together (Wild, 1993). Additionally, improved structure increases pore space, which in turn increases the water-holding capacity of soils, helping soils absorb water faster, and retain more water, longer (Brouwer et al., 1985; Wild, 2003). Increased pore space also allows for easy penetration of plant roots and creates a hospitable environment for microorganisms, fungi, bacteria, earthworms, insects and small mammals that play a vital role in cycling nutrients and maintaining soil fertility (Wild, 1993, 2003).

Air is another vital component of soil. When water enters the soil it displaces the air that is present in the pore spaces, so the amount of air present in the soil is inversely related to the amount of water in a soil (Wild, 1993). The greater the proportion of air in a soil, the greater the potential for infiltration, capture and retention of water (Brouwer et al., 1985; Wild, 1993).

All plant roots require oxygen for respiration (Wild, 2003). An exchange of gases between the roots underground and the air above ground is required for optimum plant growth (Letey, 1985). Air found within soil is very different from the air found in the atmosphere (Brouwer et al., 1985; Wild, 1993). Soil air has high humidity, oftentimes hovering around 100%. Also, while soil air’s nitrogen and oxygen levels are similar to atmospheric air, soil air may contain hundreds of times the amount of carbon dioxide due to under surface respiration of plant roots and soil organisms (Wild, 1993, 2003). Also, the greater the water content in the soil, the smaller the volume of soil air and the more quickly oxygen is depleted by plant respiration (Wild, 1993). Both of these conditions can reduce plant growth and cause plant mortality due to lack of available oxygen (Costello, MacDonald, & Jacobs, 1991; Schaffer, 2006). In an effort to restore a healthy balance of oxygen and carbon dioxide below the surface, crop growers may opt to aerate their soil through tillage. Aeration of the soil increases the availability of oxygen and nutrients and increases the ability of roots to move through the soil (Wild, 1993).

Bulk density refers to the ratio of the mass of dry soil to its volume (Wild, 1993). The bulk density of soil is a measure of the pore space and degree of the compaction of the soil (Wild, 2003). A compacted soil with less pore space has a higher bulk density, while increased pore space results in lower bulk density of the soil (Brouwer, 1985; Wild 1993, 2003). The improved soil structure associated with increased organics in a soil also results in lower bulk density, which increases the water-holding capacity of the soil (Brouwer et al., 1985; Buol et al., 2003). High bulk density soils have reduced pore space, lower infiltration rates, reduced water-holding capacity and increased surface run-off (Wild, 2003).

Soil Texture

Soil texture refers to the relative proportions of clay, silt and sand in a soil (Brady & Weil, 2000; Wild, 2003). Sand ranges in size from 2.0 mm to 0.05 mm, can be seen with the naked eye and has a low water-holding capacity (Brouwer et al., 1985). Silt ranges in size from 0.05 mm to 0.002 mm, cannot be seen with the naked eye and increases the water-holding capacity of soil (Wild, 1993). Clay is the smallest soil particle with a size below 0.002 mm. It has a high water-holding capacity and has the ability to attract and hold soil nutrients (Brouwer et al., 1985; Wild, 1993). Gravel is more than 2 mm in size, can be easily seen with the naked eye, and decreases the water-holding capacity of a soil (Wild, 2003). It is used as a textural modifier in describing soils.

Pore space in the soil is either occupied by water or air. The degree to which soil texture affects soil moisture infiltration and retention depends on the ratio of coarse and fine particles (Unger, 2002; Wild, 2003). Coarse-textured soils, such as gravelly sands, usually absorb water quickly, while finer textured soils, such as clay, take on water more slowly (Laity, 2008). Medium textured soils, such as silt loams and high-silt soils, contain the greatest amount of available water for plants (Donahue, 1983). This is because water does not percolate very deep in these soils due to capillary tension, resulting in approximately half of the soil water in the profile being available for plant use (Kopec, 1995). Both soil texture and structure have an effect on how water and air move in the soil as well as the suitability of the soil for plant growth (Brady & Weil, 2000; Strangeways, 2003; Unger, 2002; Wild, 2003).

Soil Structure

Soil structure refers to the arrangement of soil particles (Buol et al., 2003). The aggregates formed by these arrangements are known as peds, e.g., granular, blocky, prismatic, and massive peds (Brouwer et al., 1985; Buol et al., 2003; Wild, 2003). Soil particles with a granular structure are loosely packed together in small crumbly soil aggregates. This structure is often found in surface soils with high organic content (Brouwer et al., 1985; Wild, 1993). Water and air move freely in granular soils (Wild, 1993). Soil particles with a blocky structure are packed together in larger block shaped aggregates, and are found where clay is present (Buol et al., 2003). Drainage is often impaired in blocky soils due to the structure and the clay content of the ped (Wild, 1993). Prismatic structure refers to soil particles packed together in a column shape. This structure is often found where clay is present. Water movement is restricted and drainage is poor (Brouwer et al., 1985; Wild, 1993). Platy structure refers to a ped that is flat and horizontally oriented. This structure usually occurs as a result of surface compaction, which compresses the ped into a platelike formation (Buol et al., 2003). Massive structure refers to soil particles packed tightly together in one big mass, which greatly restricts water movement in the soil due to reduced pore space (Brouwer et al., 1985). While soil texture is permanent, soil structure can be altered through cultivation (Wild, 1993).

Water Cycle Variables

Precipitation

Precipitation is the main factor influencing plant growth in dryland ecosystems (Coronato & Bertiller, 1996). Precipitation in semi-arid regions is generally low in volume, erratic low in frequency, and often high in intensity (Unger 2002; Wainwright et al., 1999). During a precipitation event, a portion of the precipitation will recharge the soil profile, a portion will be evaporated, or transpired by plants and a portion may run off the soil surface (Wild, 2003).

Efficient absorption and retention of available precipitation in the soil in dryland farming environments is the key to successful crops (McCall & Wanser, 1924; Turner, 2004). The amount, timing, and distribution of precipitation have the most direct effect on soil moisture capture and retention (Coronato & Bertiller, 1996; Phillips & Phillips, 1984). The annual rainfall of a region, length of the rainy season, and the number of days between rainfall events all have an effect on the amount of precipitation that will infiltrate into the soil. In general, more precipitation translates to higher soil moisture content in the soil (Wild, 2003). Burr (1914) found that for dryland regions, the length of time between precipitation events and soil moisture are inversely related, showing that the less time that passes between precipitation events, the more moisture is retained in the soil, and vice versa. This is the case because more frequent precipitation counteracts evaporative effects (Rodriguez-Iturbe & Porporato, 2004). Distribution of precipitation refers to how far a precipitation event is spread out, and is as important to soil moisture storage as the total amount of rain received (Burr, 1914). Dry soil has a higher infiltration rate than wet soil. Water fills pore spaces of dry soil more easily than the water-filled pore spaces of wet soil (Brady & Weil, 2000; Brouwer et al., 1985; Wild, 1993). Precipitation will infiltrate easily into dry soil, but as the soil becomes wet, the infiltration rate will decrease and runoff will increase (Brouwer et al., 1985). Intense precipitation, such as localized thunderstorms, can result in increased infiltration and saturation of the soil until it reaches field capacity, after which additional precipitation results in increased surface runoff (Rodriguez-Iturbe & Porporato, 2004; Wild, 1993).

Reduction of runoff is one of the main methods for conserving water in low rainfall regions (Wild, 2003) Under the summer fallow system, precipitation during the fall, winter and early spring appears to be the most important to soil moisture storage (McCall & Wanser, 1924). In addition to intensity of precipitation, Lindstrom et al. (1974) found that type of precipitation over the winter also had an effect on soil moisture storage. They found that precipitation in the form of snow was more effectively absorbed into the soil. This was explained by the slow release of water as snow melted and the ground thawed. Winter rain tended to run off frozen soil, rather than be absorbed.

Many mid-latitude dryland farming areas receive a significant portion of their annual precipitation as snowfall (Unger et al., 2006). Snow increases the albedo of the surface, which results in reduced soil temperatures (Chung & England, 2006). In order to improve soil moisture, both the snow and the meltwater must be captured (Chung & England, 2006; Unger et al., 2006). Snow is often accompanied with wind in dryland environments, and many of the same methods used to reduce soil erosion from wind can improve snow catch (Unger et al., 2006).

Unger et al. (2006) found that the standing stubble of NT fallow greatly improves snow catch when compared to the bare soil of CT fallow. They found that while taller stubble traps and holds more snow, there is an optimum stubble height that maximizes soil moisture capture and retention. Snow trapped in taller stubble melts quicker, which results in greater runoff due to deceased infiltration time.

In Eastern Washington soils can freeze to 10 cm several times during the winter, and sometimes as deep as 40 cm (McCool, Huggins, Saxton, & Kennedy, 1999; Papendick, 1996; Papendick & McCool, 1994). Throughout the winter soils thaw partially or completely between freezing events, which affects infiltration of precipitation into the profile (Schillinger & Wilkins, 1997). If the soil is saturated or frozen, water will runoff at the surface, rather than infiltrate into the profile (Wainwright et al., 1999).

Infiltration

When precipitation falls on the surface, it can do one of two things: run off or infiltrate into the soil profile (Wild, 2003). When moisture infiltrates into the soil it displaces the air occupying the pore space between soil particles (Brady & Weil, 2000, Buol, et al., 2003). The bulk density of soil has a direct effect on infiltration (Wild, 1993). The size and number of pore spaces determines the water-holding capacity of a soil. Soil compaction reduces available pore space, while tillage can increase pore space, and therefore, water-holding capacity of a soil. Infiltration occurs in soil that has enough available storage capacity to accommodate the water from a precipitation event. If the rainfall exceeds the available storage, excess water will runoff at the surface (Rodriguez-Iturbe & Porporato, 2004; Wild, 1993).

Wind

Winds are common in arid, semi-arid and sub-humid areas (Cornelius, 2006; Nicholson, 2011). Winds decrease soil moisture by increasing evaporation at the soil surface (Nicholson, 2011). The loosely consolidated, dry soils, and sparse vegetative cover common in drylands increase soil erosion in these areas, especially of the finer textured sediments (Cornelius, 2006). Wind erosion results in dust storms, loss of soil quality, and reduced productivity (Chepil, 1956; Cornelius, 2006). Chepil (1956) stated that the degree of erodibility of the soil was directly proportional to the water content. He found that wet soils were resistant to movement, while soil particles that were dried by wind first moved easily.

Wind also has an impact on where snow occurs on the landscape (Unger et al., 2006). Wind interacts with snow particles much in the same way it interacts with soil particles, and can move snow a great distance (Chung & England, 2006). Wind influences can impact snow depth, as well as the amount of available melt water within agricultural fields (Chung & England 2006; Siddoway, 1970). Snow depths can vary depending on wind speed and direction, amount of open space, and degree of vegetative cover (Siddoway, 1970). Vegetative cover can reduce ground level wind speeds, which in turn reduces evaporative losses (Unger et al., 2006). Additionally, vegetation traps the blowing snow, deepening snow cover and improving soil moisture (Chung & England 2006; Siddoway, 1970; Unger et al., 2006).

Evaporation

Evaporation is the process in which liquid water is converted to water vapor and removed from the evaporating surface (Brouwer & Heibloem, 1986). Factors that determine the rate of evaporation from the soil surface are temperature, wind velocity, relative humidity of the air, and the albedo of the soil surface (Brouwer et al., 1985; Brouwer & Heibloem, 1986; Wild, 2003). Evaporation happens more readily when temperatures are warmer as well as in the presence of wind (Brouwer & Heibloem, 1986; Strangeways, 2003). Evaporation is a vital component of the water cycle, with an estimated 10% of the moisture found in the atmosphere coming from plant transpiration and the remaining 90% coming from evaporation from land and water sources (USGS, 2011).

Evaporation can significantly impact the amount of moisture in the soil (Buol et al., 2003; Brouwer et al., 1985). Studies have shown that in farmland evaporation mostly occurs from the top 15-20 cm of the soil (Carder & Hennig, 1966). Loss of water through evaporation is particularly detrimental to plants in low rainfall regions where evaporation rates are high due to due to high solar radiation, clear skies, and low humidity (Wainwright et al., 1999; Wild, 2003). Shading and vegetative cover can decrease the amount of evaporation of moisture from the soil (Brouwer & Heibloem, 1986;

Wainwright et al., 1999). Organic mulches decrease evaporation rates by lowering the soil temperature beneath the mulch and reducing wind speed at the soil surface (Unger, 2002; Wild, 2003). Crop residues also reduce surface runoff allowing more time for infiltration and protect the soil surface from raindrop impact and surface crusting (Unger, 2002).

Topography Variables

Topography consists of three factors: slope angle, aspect, and elevation (Hawley, Jackson, & McCuen, 1983). Slope angle influences both infiltration of precipitation and runoff (Churchill, 1982; Hawley et al., 1983). Coronato and Bertiller (1996) found topography has an effect on moisture infiltration and also plays an important role in the spatial variation of water content in the soil.

Summit, shoulder, back slope, foot slope and toe slope are the five general slope positions (McConkey, Ulrich, & Dyck, 1996). Each slope segment has different infiltration characteristics based on the duration of water contact with the soil surface, soil texture, and vegetative cover (Brady & Weil, 1999; McConkey et al., 1996). Typically, water gathers at the summit, travels over the shoulder, back slope, and foot slope, and collects in the toe slope (Buol et al., 2003). Both the summit and the toe slope segments have relatively level surfaces, which allows for infiltration, while the mid-slope areas are generally steep, resulting in less infiltration and more runoff (Coronato & Bertiller, 1996; United States Congress, 2005). In wet mountain environments, slope position has been shown to impact infiltration rates with varied results. Grah, Hawkins, and Cundy (1983) found infiltration capacity to decrease downslope, while Dunne, Zhang, and Aubry (1991) found increasing infiltration downslope. Differences were attributed to variation in vegetative cover, soil texture, and soil organic matter. Rockström and de Rouw (1997) also found a difference in soil moisture between the summit and toe slope positions during very wet periods in the Sahel, but the difference decreased with decreasing precipitation.

Aspect refers to the horizontal direction to which a slope faces (Hawley et al., 1983). Aspect has an influence on the amount of moisture in the soil by influencing the rate of evapotranspiration (Hanna, Harlan, & Lewis, 1982). South-facing slopes are generally warmer and drier in the Northern Hemisphere because they receive more direct sunlight than north-facing slopes (Brady & Weil, 1999). The additional exposure to sunlight on the south-facing slopes leads to an increased warmth of the soil, which can result in higher evaporation rates than on north-facing slopes (Churchill, 1982; Hanna et al., 1982; Strangeways, 2003).

Temperature and effective moisture differences result in deeper regolith of north-facing slopes as compared to south-facing slopes, which in turn affects the way precipitation infiltrates the soil (Churchill, 1982; Hanna et al., 1982). When the soil is dry, north-facing slopes have higher infiltration capacities than south-facing slopes. Conversely, when the soil is wet, north-facing slopes often have lower infiltration capacities than south-facing slopes, resulting in greater runoff (Churchill, 1982; Coronato & Bertiller, 1996). North-facing slopes dry more slowly and retain higher moisture levels longer than south-facing slopes (Churchill, 1982; Hanna et al., 1982).

Land Use Variable

Wheat Production

Soil moisture is the most important factor influencing seedling growth in dryland environments. There must be enough moisture in the soil at the time of seeding for seeds to germinate and seedlings to emerge and thrive (McCall &Wanser, 1924; Mahdi, Bell, & Ryan, 1998; Shunqing, Gengshan, & Anhon, 2003; Brady & Weil, 2000). In semi-arid and arid environments, the available soil water at time of sowing is critical to the success of a wheat crop (Mahdi et al., 1998; Shunqing et al., 2003). Available soil water is the total amount of water potentially obtainable by the wheat plant minus water remaining in the soil profile at harvest (Schillinger et al., 2008). Shunqing, et al. (2003) found that if available soil water is less than 200 mm, wheat seedlings would not survive the winter.

Stored soil water at time of seeding has been shown to significantly impact grain yields in dryland environments (Amir et al., 1991; Mahdi et al., 1998). Carder and Hennig (1966) found that using a three-year average, winter wheat used 26.4 cm of water from time of planting until harvest and that this wheat yielded 44.1 bushels per acre of grain. Schillinger, et al. (2008) found that after using the water available for vegetative growth, wheat produces approximately an additional two bushels per acre for each additional centimeter of water available. Donahue (1983) found that it takes approximately 10 cm of available water to grow wheat plants from seed to maturity. Further, they found an increase of 4 to 7 bushels of wheat per acre with each additional 2.5 cm of moisture available in the soil. Wheat yields also increased with additional moisture in a study by Shunqing, et al. (2003), who found an increase of 11 bushels per acre with an additional 5 cm of available soil water.

Summer Fallow

Cereal crop production is highly dependent on the amount of water stored in the soil profile at time of seeding (Stewart, 2009). This is because there is not sufficient precipitation during the growing season to produce a viable crop. In many dryland wheat-producing areas, the dominant crop rotation is winter wheat/summer fallow, in which one crop is produced every other year (Schillinger et al., 2008). For example, a given field is planted in September of year one, grows throughout the year and is harvested the following July or August. After harvest, the field is left unplanted until September of year three, resulting in one crop every two years.

Because precipitation in dryland areas is variable, storage of sufficient water in the soil is highly important for minimizing water stress on crops during growing season (Unger, 2002). The summer fallow system is regarded as the best way of improving the soil moisture content for cereal crops (Amir et al., 1991). The goal of the summer fallow system is to store a portion of overwinter precipitation in the soil to aid in the successful establishment of wheat at the time of planting (Schillinger & Young, 2004; Stewart, 2009). While the land lays unplanted, or fallow, the moisture that would otherwise be used by crops accumulates beneath the surface, which increases soil moisture storage (Bewick, Young, Alldredge, & Young, 2008; Amir et al., 1991).

Under the summer fallow system, Burr (1914) found that during a high precipitation year in Nebraska, the soil stored 33% of the rainfall from one season. In years of less precipitation, the storage rate was 10%. This finding is supported by Wuest & Schillinger (2011) who found during their 6-year study in Lind, Washington, that the average precipitation storage during fallow ranged from 33% (under no till) to 40% (under conventional tillage).

Choice of land-use method is extremely important in a water-limited, dryland environment (Lawrence, Radford, Thomas, Sinclair, & Key, 1994). In the dryland areas of the Pacific Northwest, winter wheat is primarily grown under two tillage methods: conventional tillage (CT) and no tillage (NT). Tillage can affect many properties of the soil, including: organic matter, moisture, erosion potential, temperature, and density (Griffith et al., 1986). Choice of tillage method can also have an impact on soil moisture losses to evaporation (Unger, 2002). Conventional wisdom holds that when the ground is broken up, precipitation will more easily find its way deep into the soil. Conversely, the more surface area that is exposed to air, the more moisture will eventually evaporate. Here lies the conundrum: to till or not to till. In an effort to reduce erosion and maintain a healthy ecosystem in agricultural areas, some lands are left untilled and allowed to grow native vegetation under the Conservation Reserve Program (CRP).

Conventional Tillage

The CT method includes fall and/or spring plowing (Phillips & Phillips; 1984). During the 12-month fallow period, farmers make between four and eight passes over the fields with plows, chisels, disks, field cultivators, harrows and rollers to prepare the seedbed for planting (Griffith et al., 1986; Schillinger et al., 2006). While the initial use of the moldboard plow creates random surface roughness, which greatly increases infiltration, subsequent tillage, such as disking and harrowing has been shown to reduce pore space and surface roughness, leading to decreased infiltration (Unger et al., 2006). Multiple field operations with heavy equipment can reduce macropore space through compaction, which will reduce the water-holding capacity of the soil as well as reduce infiltration (Unger et al., 2006; Wild, 2003). The smaller pore space of compacted soil makes it harder for roots to move through the soil and decreases the rate of infiltration and drainage in high bulk density soils (Wild, 2003).

Most tillage systems severely limit plant diversity in favor of a single crop species (Legere, Stevenson, & Benoit, 2005). Despite this fact, weed species persist in cultivated areas. Machado, Jakelaitis, Ferreira, Agnes, and Santos (2005) found that weed population dynamics can be attributed to the type of tillage, and that different weedy species are better suited for different tillage practices. The soil management characteristics between CT and NT alter the physical and chemical properties of soils that can be favorable to the germination of various weedy species. CT and NT have different aeration and soil moisture characteristics associated with them, which will influence the weed species that are present.

The presence of weeds has been shown to reduce soil water during fallow (Unger et al., 2006). CT effectively uses tillage to remove weeds that directly compete with a crop for soil moisture, nutrients, and light (Schillinger, 2001; Unger et al., 2006). Tuesca, Puricelli, and Papa (2001) found annual weeds in higher densities in CT fields. This was explained by the fact that CT tillage occurs every year and annual plants complete their life cycle within one year.

Additionally, CT tillage practices mix nutrients deeper into the soil and aerate the soil, allowing moisture and oxygen to penetrate to the roots (Phillips & Phillips; 1984, Schillinger et al., 2006). These tillage practices incorporate surface residues, such as weeds and stubble left after harvest, into the soil, and leave a dust mulch on the surface

(Schillinger, 2001). During CT fallow, residues are buried and surface structure and roughness are reduced through multiple tillage practices (Schillinger, 2001). These practices were developed to break the capillary continuity between the soil surface and the subsoil by creating a dust mulch barrier at the surface that reduces evaporation and conserves moisture in the seed zone (Bewick et al., 2008; Riar, Ball, Yenish, Wuest, & Corp, 2010). This tillage practice breaks up the soil peds and leaves a powdery mulch at the surface which can be easily eroded by wind and water (Schillinger & Papendick, 1997). Erosion of the more fertile surface horizons can decrease fertility, requiring the need for more fertilizer (Riar et al., 2010).

In a low precipitation region in Eastern Washington, CT fall tillage increased overwinter water storage, especially in colder years, compared to mild winters. This was attributed to improved infiltration of frozen soil due to surface disturbance, and the differences in type of precipitation during cold and mild winters. They also found that a dust mulch was beneficial to retention of soil water below mulch during dry summer (Linstrom et al., 1974). Unger et al. (2006) found that while soil crusting is reduced in CT by breaking up the surface crust with tillage, allowing precipitation to infiltrate, tillage increased evaporation by exposing moist soil to the atmosphere, causing water loss.

A disadvantage of the tillage operations associated with CT is that they disrupt the life cycles of beneficial organisms, such as earthworms (Burke, Lauenroth & Coffin, 1995; Kok et al., 2009; Triplett & Dick, 2008). Earthworm burrows increase macropore space, which allows precipitation to infiltrate deeper into the profile (Edwards, Shiptalo, Owens & Dick, 1992; Kok et al., 2009). Edwards et al. (1992) found significantly fewer burrows in conventional tillage fields when compared to NT. This was attributed to the low disturbance of NT creating a more favorable environment for burrowing animals than the high disturbance of CT.

No Tillage

NT is promoted as a sustainable and environmentally-friendly system that increases surface roughness, soil water infiltration, and soil water storage, while reducing production cost, evaporation, seed zone moisture loss, and soil erosion during fallow (Bescana, Imaz, Vitro, Enrique, & Hoogmoed, 2005; Schillinger, 2001). Given the current economic conditions, the lower fuel and labor costs associated with NT make it an attractive option to increase the profitability of agricultural operations (Riar et al., 2010). The NT method involves minimal soil disturbance throughout the growing season and retains standing stubble from the harvested crop throughout the fallow period (Coleman, 2003). Plant residues left on top of the soil and dead root systems left within the soil have been found to increase soil moisture by increasing pore space, which allows more room for water infiltration (Coleman, 2003, Unger et al., 2006).

Studies have shown an increase in soil organisms, nutrients, and soil moisture with NT (Coleman, 2003; Riar et al., 2010). Standing stubble mulch has been found to be an effective method of conserving water in the seed zone area, by shading the soil surface and reducing evaporation (Lindstrom et al., 1974). The mulch also facilitates infiltration of precipitation and reduces runoff. NT systems that leave more than 50% surface residue significantly increase soil moisture and decrease evaporation (Griffiths et al., 1986). The stubble catches and retains precipitation, and facilitates infiltration of snowmelt during freeze-thaw periods (Lindstrom et al., 1974). Stubble mulches decrease evaporation rates by lowering the soil temperature beneath the mulch and reducing wind speed at the soil surface (Unger, 2002; Wild, 2003).

During the fallow period of NT it is imperative that soil water use by weeds be eliminated or minimized to obtain optimum soil water storage. Weeds reduce soil water during fallow and compete directly with crops for soil moisture during the growing season (Unger et al., 2006). Instead of using tillage to control weeds, NT uses herbicides, which have been shown to increase soil moisture (Riar et al., 2010; Stewart, 2010). This is likely due to the prompt removal of weeds, allowing water to stay in the soil, rather than being transpired by the plants.

A study by Tuesca et al. (2001) found perennial weeds in higher densities in NT fields. Perennials have indeterminate life cycles, which allow them to establish a large root system and re-grow year after year (Ramamoorthy, Lourduraj, Thiyagarajan, Prem Sekhar, & Stewart, 2004). NT leaves the soil undisturbed for longer than one season, which can allow perennial weeds to take hold. Additionally, perennial vegetative cover has a much higher evapotranspiration (ET) rate compared to annual row crops. Perennial vegetation transpires throughout the spring, summer and fall, compared to row crops where the substantial transpiration occurs mid-growing season (Zhang & Schilling, 2006). Tuesca et al. (2001) also found higher densities of wind-disseminated species in NT fields. This was attributed to the fact that the crop residues associated with NT trap the seeds as they blow around and allow them to establish in the field.

Stubble mulches also reduce surface runoff, which increases infiltration and protects the soil surface from raindrop impact and surface crusting (Unger, 2002; Unger et al., 2006). FAO (2011) states that the stubble mulch of NT fallow increased the water in the soil by 4%, which equates to approximately 8 mm of additional rainfall in a crop year.

Blevins, Smith, and Thomas (1971) found that NT plots had 19% higher soil moisture content in the 0-15 cm depths than CT plots, which was attributed to the presence of surface residues. Supporting the supposition that surface residues decrease evaporation of soil moisture, Phillips and Phillips (1984) found that with an increase in frequency of rainfall events, evaporation of soil moisture in NT fields was less than in CT fields. Shading and a higher albedo at the surface resulted in a lower soil temperature beneath the mulch. Additionally, reduced wind speed at the soil surface helped retain precipitation moisture longer (Unger, 2002; Wild, 2003).

While NT can increase soil moisture, there are some instances where it has been shown to decrease soil moisture. In Eastern Washington, frost may penetrate to 30 cm or more, but alternate freeze-thaw periods are common through the winter into early spring (Linstrom et al., 1974). A comparison of cumulative precipitation and water storage on CT and NT lands indicated that the major loss of soil water occurs during late winter and early spring, when there are warming trends, the soil surface is still wet much of the time, and evaporation rates increase (Bescana et al., 2005). Under NT, a major portion of soil moisture recharge from fall and winter precipitation is lost during the summer due to upward capillary flow/evaporation from soil or transpired by weeds (Riar et al., 2010; Schillinger & Bolton, 1993).

A study in Eastern Washington by Heer and Krenzer (1989), found that when CT and NT monoculture wheat were planted at the same time, soil water was greater under

NT. This was attributed to the lower soil temperatures found under NT stubble mulch fallow when compared to CT bare soil fallow, which reduced evaporative losses.

Regarding the comparison of crop yields between the two tillage methods, both length of time under a certain tillage method and amount of precipitation will provide varied results. Many studies have shown that after an initial lower yield in the NT method, yields increase and become comparable to CT after one to three years (Olson et al., 2004). While crop yields of both tillage methods varied due to weather fluctuations during their 20-year study, Olson and Ebehar, (2009) found that the initial low yields of NT improved as the soil organic carbon increased. Lawrence et al. (1994), also found that the initial lower yields after switching to NT were likely due to lower soil organics and nitrogen mineralization, which improved with time. The retention of surface residues under NT increased organics in the soil, while reducing erosion of the surface layer. This improved soil nutrient availability, as well as the water holding capacity of the soil, leading to increased yields after only a few years (Olson et al., 2004; Olson & Ebelhar, 2009).

Of importance to drylands such as the study area, both Lueschen, Evans, Ford, Hoverstad, and Kanne (1991) and Heer and Krenzer (1989) found that wheat yields under NT were higher than wheat yields under CT during years of lower precipitation. This is supported by Blevins et al. (1984) who found that NT uses stored soil water more efficiently than CT during short-term droughts.

Conservation Reserve Program

Not all farmland is actively being farmed. Some lands are set aside for conservation purposes. The United States has a long history of involvement in the area of conservation (Lowitt, 1985; Napier, 1997). Numerous programs have been implemented specifically to protect soil quality and reduce erosion on agricultural lands (Sharratt, Feng & Wendling, 2007). The most recent is the Conservation Reserve Program (CRP). The CRP is a voluntary program that provides technical and financial assistance to eligible farmers and ranchers to reduce soil erosion and sedimentation, improve soil and water quality, and improve wildlife habitat (Dunn et al., 1993; Batie, 1985; Macinko, 1985)

The destruction of millions of acres of agricultural land during the Dust Bowl years of the 1930s and the economic plight of famers in the ensuing depression caused Congress to pass legislation to financially assist farmers with conservation of farmland. The intent was to reduce the rate of erosion in agricultural lands as well as protect agricultural productivity and farm income (Batie, 1985; Lowitt, 1985; Napier, 1997). Farmers were encouraged to remove fields from cultivation, plant native vegetative cover, and curb cultivation of erosion prone crops in exchange for financial incentives (Batie, 1985). In the 1940s, Farm Bill legislation encouraged farmers to remove land from cultivation regardless of the condition of the soil, a measure that helped to stabilize commodity prices (Batie, 1985; Napier, 1997). During the 1950s, farmers removed land from production to control the supply of commodities as well as protect soil quality. This began the implementation of 10-year conservation contracts between farmers and administering entities (Batie, 1985). New legislation in 1977 mandated only lands threatened in some way by erosion were eligible for the programs (Batie, 1985; Napier, 1997).

CRP was established a part of the Food Security Act (1985). CRP provided funds for the government to implement conservation measures on highly erodible farmlands.

The goal of the program was to help farmers protect environmentally sensitive lands by reducing soil erosion, improve water and air quality, and enhance wildlife habitat (Cowan, 2010). Under CRP these lands were taken out of production for 10 years at a time (Napier, 1997). The lands were then planted to native perennial vegetation on any acreage enrolled in the program (Cowan, 2010; Napier, 1997).

Erosion remains the main determining factor in whether a farmer can participate in conservation programs on agricultural land (FSA, 2012). Today, while under CRP contract for between 10-15 years with the Farm Service Agency (FSA), fields are converted to annual and perennial plants and left undisturbed. In return for leaving the land unfarmed farmers receive an annual rental payment (Batie, 1985; Dunn et al., 1993; FSA, 2012; Macinko, 1985).

The soils of CRP fields have reduced compaction and increased pore space when compared to tilled fields, which increases water infiltration and storage (Johnson & Quarles, 1998). The higher organic content associated with CRP fields increases water-holding capacity and tilth in the soil (Vrtiska, 2003). The improved soil structure associated with increased organics in a soil also results in lower bulk density, which is beneficial to plant growth and root movement (Brouwer et al., 1985). Low bulk density soils create a hospitable environment for soil dwelling creatures such as insects, earthworms, mice, and gophers (Edwards et al., 1992). The presence of burrows and cavities under the surface increase pore space within the profile, allowing for additional water infiltration and storage, when compared to areas without burrows (Edwards et al., 1992; Laundre, 1998).

Switching land from crop production to the grass and shrub cover of CRP can increase evaporative losses. The grasses and shrubs on CRP land are generally perennials, which have a higher evapotranspiration rate than crops (Napier, 1997). Perennial vegetation transpires from early spring through fall, while crops mostly transpire during the middle of the growing season (Zhang & Schilling, 2006). CRP has also shown to reduce evaporative losses when compared to bare soil (Johnson & Quarles, 1998). The vegetative cover of CRP increases the surface albedo and shades the soil surface, which lowers the temperature of the soil beneath the vegetation (Vrtiska, 2003). Additionally, vegetation decreases wind speed at the surface, which also reduces evaporation (Johnson & Quarles, 1998; Vrtiska, 2003).

CHAPTER III

STUDY AREA

Location

The study area is on the Waterville Plateau, part of the larger Columbia Plateau that includes the states of Washington, Oregon, and Idaho (Shepard, 2006). The Columbia Plateau lies between the Cascade Range and the Rocky Mountains, and covers an area of approximately 73,000 km^2. The Waterville Plateau is bordered by the Grand Coulee to the east, the Columbia River to the north and west, and the Quincy Basin to the south (Baker, 1933).

Located in eastern Douglas County, the 23 km^2 study area is centered in the vicinity of Mold, Washington, at latitude 47° 44' 36"N, longitude 119° 19' 05"W (T26N, R28E, Willamette Meridian), an area with an average elevation of 716 m. The study area is approximately 19 km northwest of Coulee City. Access to the study area involves taking several gravel roads from Washington Highway 17 (Figure 3.1).

Geology and Geomorphology

The geology of the study area is a result of plutonism, volcanism, glaciation, mass wasting, weathering, and wind influences. The bedrock of the area is primarily granite and basalt (Gulick & Korosec, 1990). Granite is the oldest rock in the region and underlies the entire area. This granite was intruded approximately 60 million years ago (Gulick & Korosec, 1990).

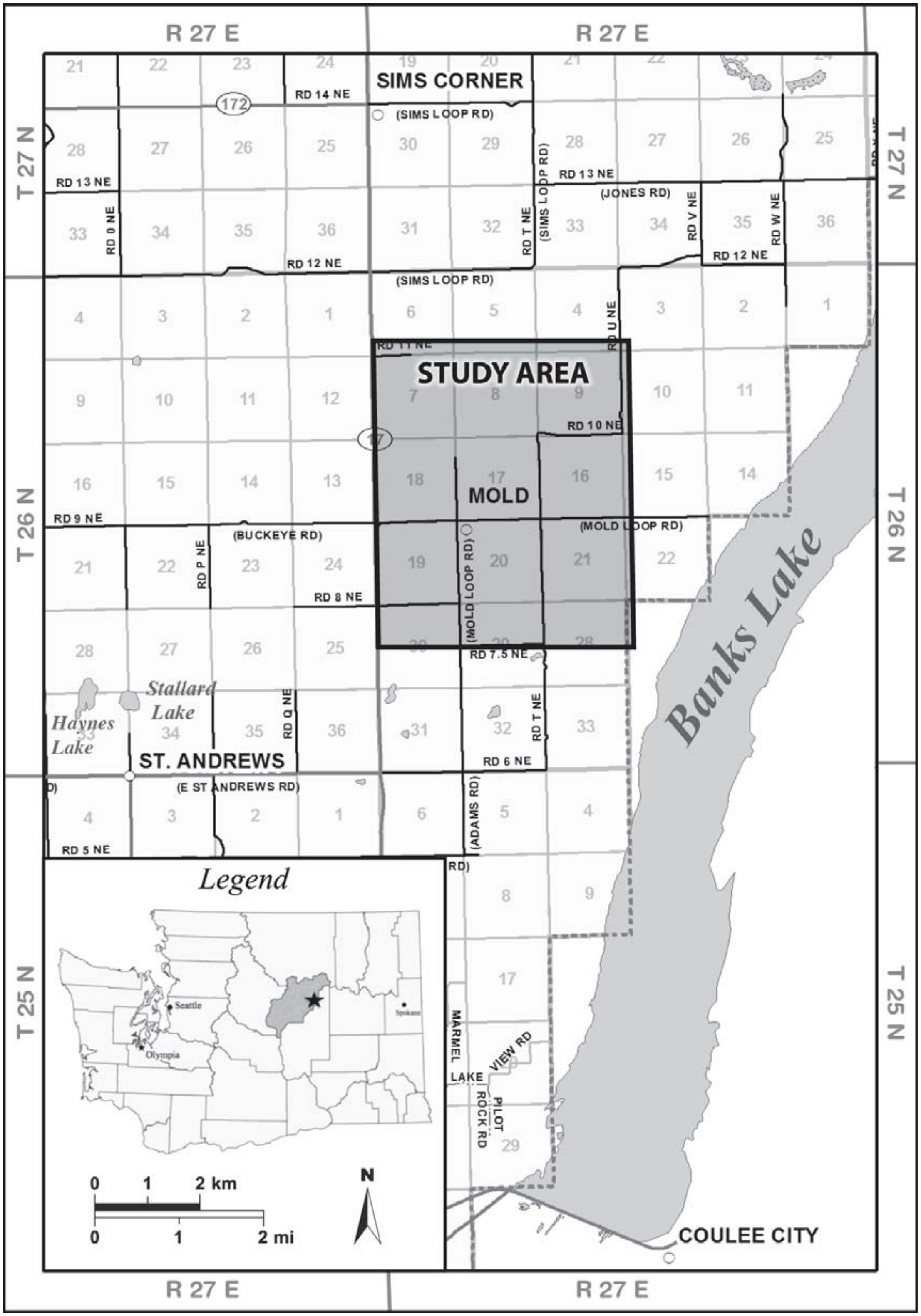

Figure 3.1. Location of study area in Eastern Douglas County, Washington (Douglas County Assessor, 2005; NRCS, 2008).

Above the granitics, the Columbia Plateau is underlain by one of the most extensive lava flows in the world, which engulfed about 163,169 km^2 of the Pacific Northwest during the middle and late Miocene periods. The Columbia River Basalt flows were active from 16 million years ago through 6 million years ago (Swanson, Cameron, Evarts, Pringle, & Vance, 1989; Gulick & Krosec, 1990). The Wanapum Basalt flow, a Priest Rapids Member, was deposited during the middle Miocene, and underlies the entire study area. The thickness of this unit is unknown (Gulick & Krosec, 1990).

During the middle to late Pleistocene, multiple periods of glaciation occurred in the region. Glacial deposits from the Pleistocene, about 2 million to 12,000 years ago, had a profound influence on the geology, geomorphology and topography of the area (Kovanen & Slaymaker, 2004; NRCS, 2008). The study area is located near the southern margin of the Okanogan Lobe of the Cordilleran Ice sheet, which deposited unsorted, non-stratified till throughout the Plateau and is responsible for the hummocky landscape that characterizes the study area (Gulick & Krosec, 1990). The Withrow Moraine, which marks the southern extent of the Cordilleran Icesheet, lies just south of the study area. Other glacial features, such as recessional moraines, drumlins, and kettles occur in the study area. In addition, glacial meltwater deposited sorted, stratified drift in the forms of kames and eskers (Gulick & Krosec, 1990; Kovanen & Slaymaker, 2004; Lillquist et al., 2009; NRCS, 2008). As the glaciers receded, meltwater deposited glacial outwash throughout the region.

During this time, loess was transported to the area by southwesterly winds from glacial outwash and glacial lake deposits in the southern part of Washington (Busacca & McDonald, 1994; Grolier, 1965). The loess was deposited over the period from more than

50,000 years ago to the present (Grolier, 1965; Kovanen & Slaymaker, 2004; NRCS, 2008).

Mass wasting and weathering also influence the geology of the area. The thin soils commonly found in drylands are particularly susceptible to mass wasting and weathering (Churchill, 1982). Mass wasting transports the material down slope by gravity and weathering works to break up the material into smaller particles (Buol et al., 2003). Slope and aspect influence the degree of mass wasting and weathering that occur (Churchill, 1982). Slope position influences both infiltration of precipitation and runoff (Churchill, 1982; Hawley et al., 1983). Steep slopes have less infiltration because of the short duration of contact, while more level surfaces have higher infiltration rates due to decreased run off and increased length of contact with the soil surface (Coronato & Bertiller, 1996; United States Congress, 2005). Increased infiltration of precipitation accelerates weathering within the soil profile and can lead to mass wasting events (Hanna et al., 1982).

Volcanic activity also played a role in shaping the geology of the area through the deposition of ash (Hanson, 1970). Located to the west of the study area, the Cascade Range contains 27 volcanoes. Many of these volcanoes have been active over the last 10,000 years, depositing ash throughout the study area (NRCS, 2008)**.** As a result, volcanic ash is present in many of the soils of the area. The most notable ash event occurred 6,850 yr BP, after the last glaciation when Mount Mazama in central Oregon erupted. Additionally, ash from the 1980 eruption of Mount St. Helens is found in the soils of the plateau, ranging in depths from trace amounts to up to 5 cm (Busacca et al., 2001).

Weather and Climate

The study area is characterized by a semi-arid, mid-latitude steppe climate with warm, dry summers and cold, wet winters. The majority of the precipitation occurs between November and March, primarily in the form of snow, which accounts for a large portion of the soil moisture in the profile (Mahdi et al., 1998, NRCS, 2008). The annual average precipitation from 1971 to 2000 was recorded as 29.3 cm (PRISM, 2011). December is the wettest month, with an average of 4.2 cm of precipitation, while the driest month is August, with an average of 1.2 cm of precipitation (Figure 3.2).

The average annual temperature from 1971 to 2000 was recorded as 8.4 °C (PRISM, 2011), with an average high temperature of 14.9 °C and an average low of 2.1 °C (Figure 3.2). The lowest mean monthly temperature (-7.3 °C) occurs in January and the highest mean monthly temperature (29.2 °C) occurs in July (PRISM, 2011). The frost-free season ranges between 130 to 180 days (NRCS, 2008).

During the winter months, the soil may freeze to the depths of 30 cm or more (NRCS, 2008). Alternating freeze-thaw periods are common through the winter and into the early spring (Lindstrom et al., 1974). Runoff, and associated soil erosion, is possible when rain falls on frozen soil or if snow melts too rapidly in spring and the water does not infiltrate the soil (Lindstrom et al., 1974; NRCS, 2008).

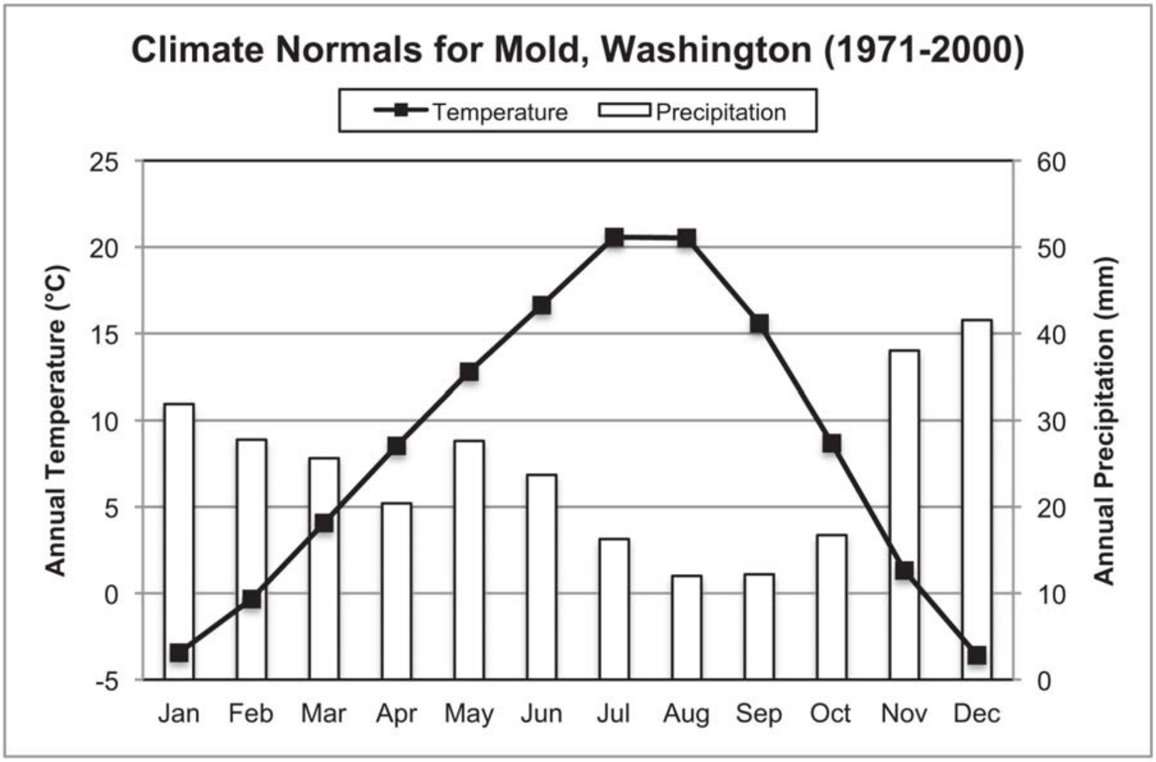

Figure 3.2. Climate normals for Mold, Washington, 1971-2000 (PRISM, 2011).

During the summer months, high temperatures help account for increased evaporation rates. Also contributing to increased evaporation are high winds from the southwest or west (NRCS, 2008). While evaporation data is lacking in this study area, nearby measurements suggest a range in the vicinity of 104 cm to 126 cm per year (Figure 3.3). Quincy, which lies 100 km SW from the study area at 395 m elevation, has a mean annual evaporation of 126 cm. Wenatchee, 119 km WSW from the study area at 238 m elevation, has a mean annual evaporation of 104 cm (Western Regional Climate Center, n.d.).

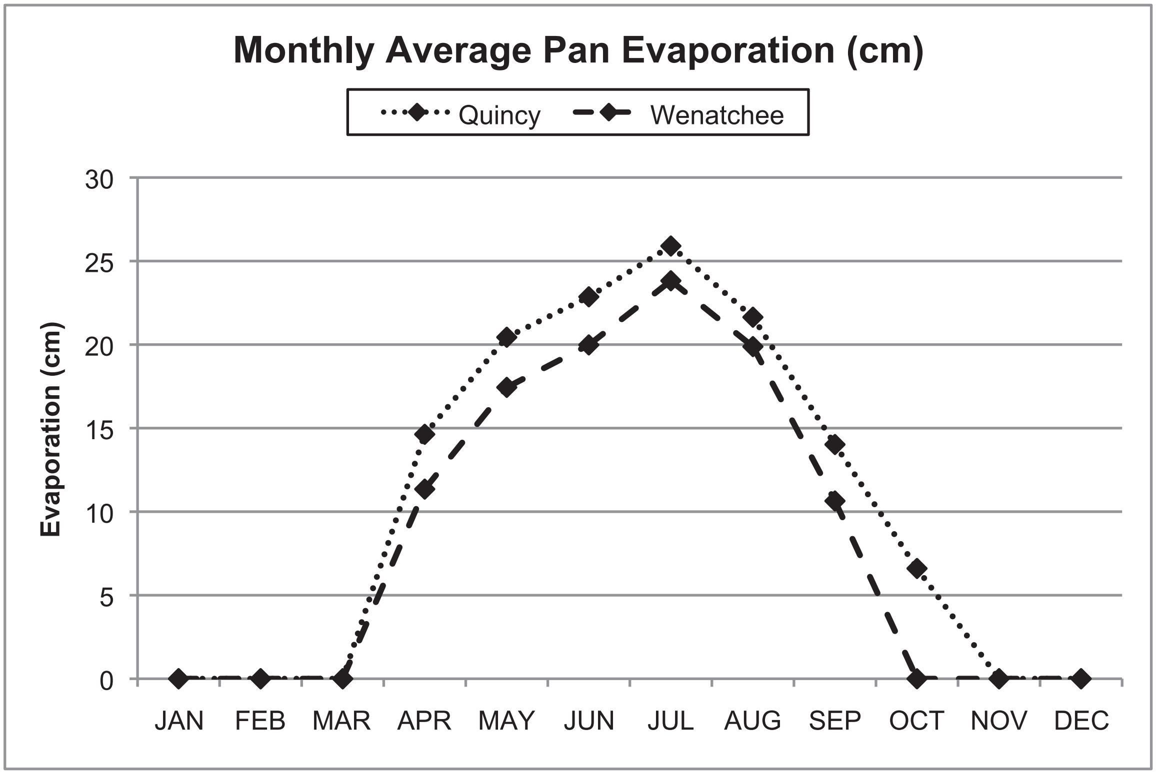

Figure 3.3. Monthly average pan evaporation in cm for Quincy (1941-2005) and Wenatchee, WA (1950-1997) (Western Regional Climate Center, n.d).

Hydrology

The study area is bordered by Foster and Moses coulees, both of which are large paleo-channels now containing very small streams (Kovanen & Slaymaker, 2004; Lillquist et al., 2009). The plateau slopes gently to the southwest, and drains in that direction (Anglin, 1995).

The hydrology of the study area is influenced by its glaciated past. The area is characterized by many closed basin wetlands receiving flow from precipitation, groundwater, and seasonal runoff (Lillquist et al., 2009; NRCS 2008). Because a significant proportion of annual precipitation falls as winter snow, spring snowmelt and runoff from frozen soil provides water inputs to ephemeral, intermittent, and perennial stream channels (Lindstrom et al., 1974, NRCS 2008). Seasonal ponds exist across the study area and their water levels fluctuate throughout the year based on temperature, precipitation, evaporation, groundwater levels, and land use (Lillquist et al., 2009).

Vegetation

The study area is characterized by native shrub steppe vegetation that is adapted to living in a low moisture environment. The dominant grasses found in the area are bluebunch wheatgrass (*Pseudoroegneria spicata*) and Sandberg bluegrass (*Poa secunda*). The principal shrubs are big sagebrush (*Artemisia tridentata*) and bitterbrush (*Purshia tridentata*). Idaho fescue (*Festuca idahoensis)*, lupine *(Lupinus spp.),* and three-tip sagebrush (*Artemisia tripartita*) are also found here in abundance. Additional vegetation in the study area includes agricultural commodities such as winter and spring wheat (*Triticum spp*.), as well as introduced vegetation in the form of CRP plantings. Invasive species such as cheat grass (*Bromus tectorum)*, dalmatian toadflax (*Linaria dalmatica*), and mustards such as Jim Hill mustard (*Sisymbrium altissimum)* are common in agricultural fields and on roadside edges (NRCS, 2008; State of Washington, 1904).

Riparian vegetation is scarce, but found around seasonal ponds and wetlands. In riparian areas, common vegetation includes sedges (*Carex spp*.), cattails (*Typha latifolia*), and occasionally willows (*Salix spp*.) (Roccohio & Crawford, 2009).

Soils

The soils of the study area vary greatly based on parent material. Most of the soils are derived from residuum, colluvium, glacial till, glacial outwash, volcanic ash, and loess (NRCS, 2008). These soils are generally well drained but shallow. Most soils in the county that formed in glacial till are covered with loess and volcanic ash deposited after the glaciers had melted (Beget, 1984). Common in the study area, the Siweeka and

Touhey series are examples of these soils (NRCS, 2008). Many of the soils in the study area are very rocky because soils formed from glacial till are often sandy and rocky. Due to the semi-arid conditions of the area, many have cambic horizons and contain a hard duripan layer within their profile (NRCS, 2008).

The Siweeka complex (see Appendix A) covers 21% of the study area and is described as ashy over loamy, glassy over mixed, superactive, mesic Vitrandic Durixerolls. This soil is classified as a mollisol and is described as a well-drained soil formed in loess and volcanic ash over glacial till over basalt bedrock (NRCS, 2008, Web Soil Survey, 2011). The soil is found at a higher elevation than the Touhey complex and is believed to receive more precipitation. The mean annual precipitation is 30-38 cm, and the depth to the duripan is 51-102 cm (Web Soil Survey, 2011). The Siweeka soil has a land capability class of 3s. Class 3 soils have severe limitations that restrict the choice of plants or that require special conservation practices, or both. The “s” indicates that the soil is limited mainly because it is shallow, droughty, or stony (NRCS, 2008).

The Touhey complex (see Appendix B) covers 28% of the study area and is described as ashy over loamy, glassy over mixed, superactive, mesic Vitritorrandic Durixerolls. This soil is classified as a mollisol and is described as a well-drained soil formed in loess and volcanic ash over glacial till over basalt bedrock. The mean annual precipitation for this soil is 23-30 cm and the depth to duripan is 51-102 cm (Web Soil Survey, 2011). The Touhey soil has a land capability class of 4s. Class 4 soils have very severe limitations that restrict the choice of plants or that require very careful management, or both. Like the Siweeka complex, The “s” shows that Touhey complex is limited mainly because it is shallow, droughty, or stony (NRCS, 2008).

Land Use

At the time of first settlement, the Columbia Salish and the Wanapam Indians resided in the area that later became known as Douglas County (Anglin, 1995). Settlers began arriving in 1877, and numbered 100 when the county was created in 1883 (State of Washington, 1904).

Land acquisition records from the Bureau of Land Management (2011) for the first settlement of the study area show 117 settlers between the years of 1891-1918. The majority of the settlement took place between 1891-1907. Homesteads ranged in size from 80-160 acres per person. The earliest pioneers in the study area raised sheep and cattle, believing that the soils were poor and not suitable for farming crops (State of Washington, 1904). This attitude changed following the harsh winter of 1889/1890, when almost all of the sheep and cattle in the county died of starvation or exposure. Rather than replace their lost livestock, many ranchers began growing wheat (Becker, 2006).

The settlement of the area has changed significantly through time. Today, there are 19 landowners within the study area. All parcels are listed as farms on the Douglas County Assessor's website (2011), with the dominant land uses for each parcel listed as rain-fed wheat, pasture, and CRP.

Wheat is the characteristic crop of the area and is farmed under the summer fallow system. Two seasonal wheat crops, spring wheat and winter wheat, are produced in the area (McCall & Wanser, 1924). Winter wheat dominates in the region, and is seeded in late August or early September. Spring wheat is seeded in April or May and accounts for a much smaller percentage of total wheat grown (WA Grain Alliance, 2011). Both types of wheat typically head out in the late spring to early summer and are ready to harvest by July or August (Simmons, Oelke, & Anderson, 1995). The parcels selected for the study exclusively grew winter wheat for the duration of data collection.

In 1904, production of rain-fed wheat in Douglas County was reported to be 30 to 50 bushels/acre under summer fallow (State of Washington, 1904). The September through June precipitation for that year in Waterville was 38.15 cm, which is above the average of 26.19 cm (FCCD, 2011). A harvest of 30 to 50 bushels/acre is not so different from today, depending on the amount of precipitation. Average yields of winter wheat in Douglas County between 1972 and 2002 were 39 bushels/acre (United States Department of Agriculture, National Agricultural Statistics Service, 2011b).

CHAPTER IV

METHODS

Study Area

The study began in September 2010 and continued until September 2011. Data collection took place on adjacent plots of land owned by two farm families in the vicinity of Mold, WA, with the McDonald family farming under conventional tillage (CT) and the McLean family farming under no tillage (NT). Each farm also contained portions of land under CRP contract, which acted as a control for the study by approximating natural conditions (Figure 4.1). Both farms grow Eltan® winter wheat on the same soil series utilizing the winter wheat/summer fallow system, in the same climate conditions. The main difference between the two farms was the tillage method.

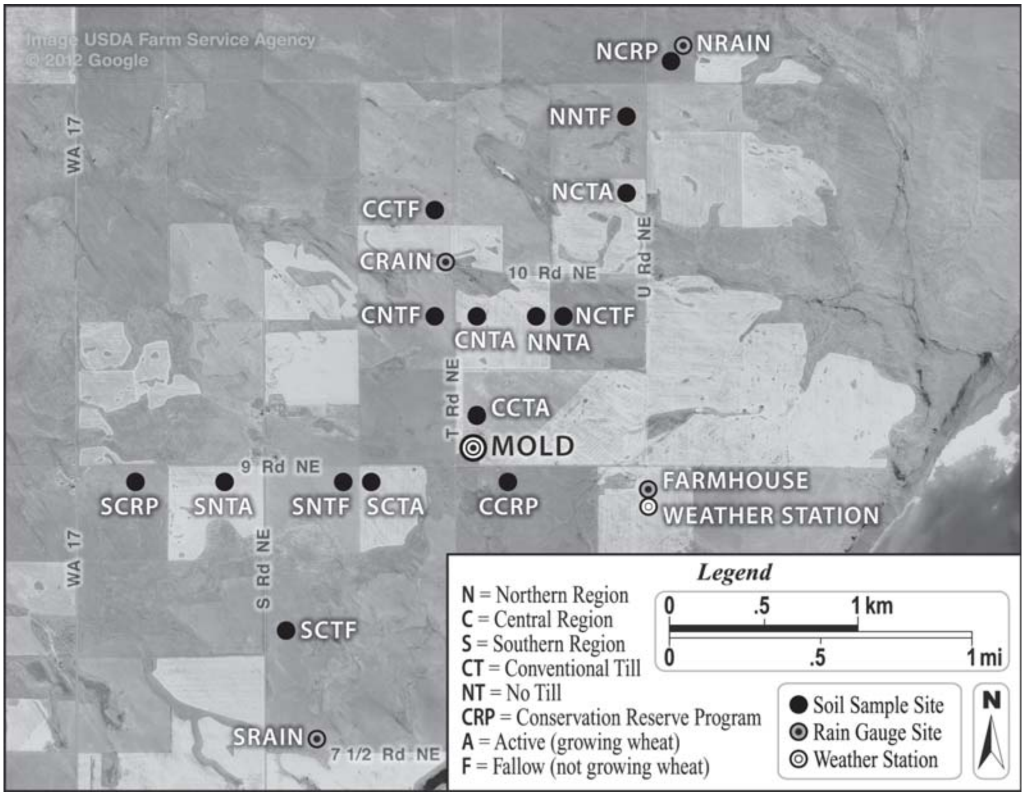
Image USDA Farm Service Agency © 2012 Google

Figure 4.1. Soil sample sites and rain gauge locations within the study area.

Site Selection

In choosing soil sample sites, it was important to select a sufficiently large sample area to accurately represent the thousands of acres of surrounding farmland. As shown in Figure 4.2, a single soil type was not available over the entire area. Because of this, Siweeka and Touhey, two extremely similar soils and the most prevalent in the area, were chosen. The study area was organized into three distinct regions (Northern, Central and Southern). Each region contained a consistent soil map unit and one of each of the five land-use types, all located in close proximity. The land-use types were: no tillage active (NTA), conventional tillage active (CTA), no tillage fallow (NTF), conventional tillage fallow (CTF), and CRP). Topography was also controlled for and standardized throughout the study, leaving land use, evaporation, temperature, and precipitation as the impacting variables on soil moisture. Data were collected at 15 soil sample sites, four rain gauge sites, and one overall weather site, which digitally recorded air temperature and precipitation.

Prior to beginning data collection, I visited the study area September 5, 2010 and September 18, 2010 to document sample site selection. At each site, I marked out a 1 m^2 quadrat, approximately sixty m into the interior of each agricultural field. I then photographed each sample site, and wrote a detailed description of each site in my field notes. I then marked each site using a GPS unit. This allowed me to precisely locate each sample site when collecting data on future trips.

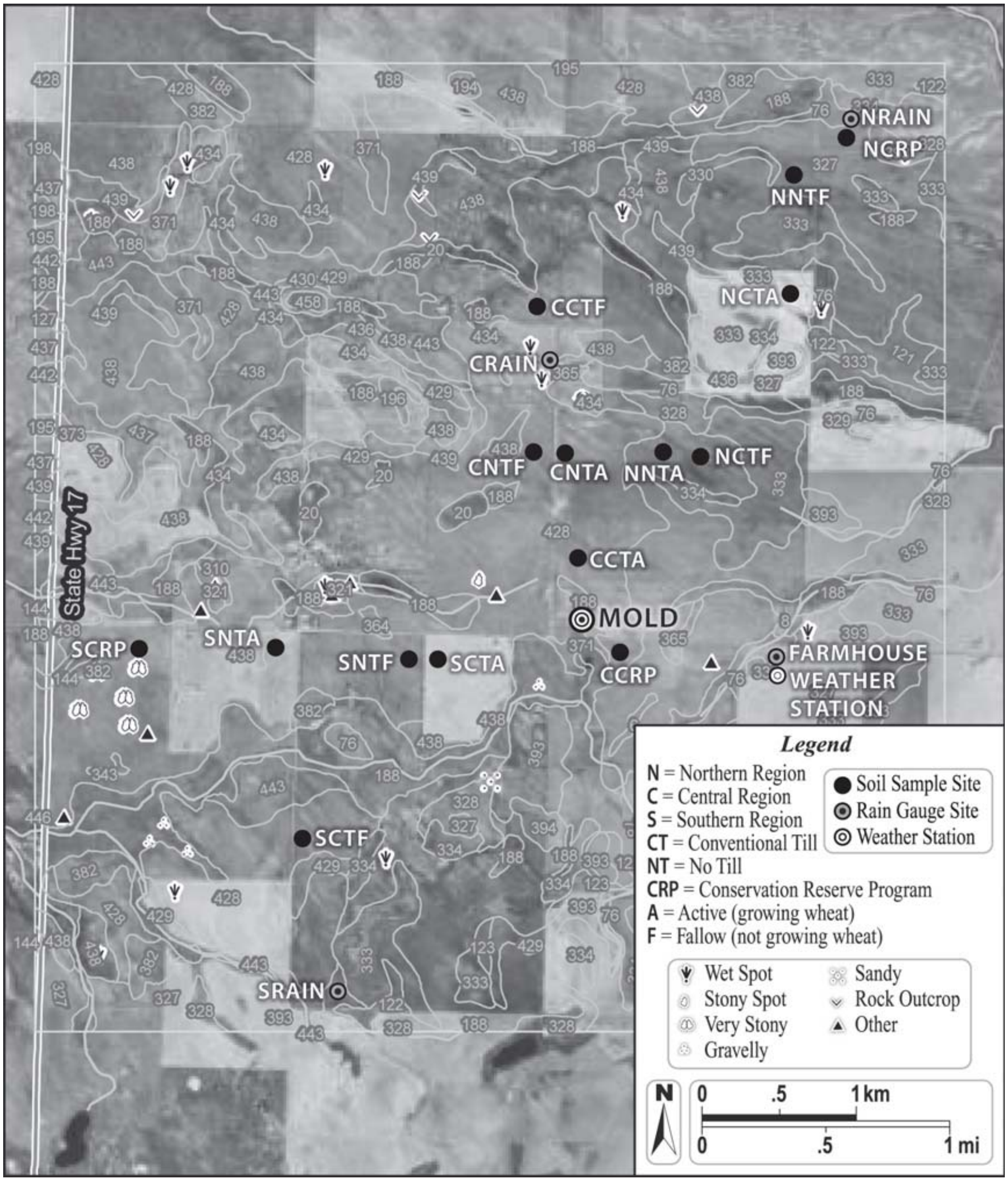

Figure 4.2. Soil map of the study area (NRCS, 2011).

Summary of Sample Site Characteristics

Sample site characteristics are summarized in Table 4.1. Due to the land use, and soil map unit requirements of the study design, both summit and toe slope positions had to be used. It was hypothesized that since slope segments on the same soil map unit should have the same intake rate, and precipitation was low in the study area, moisture differences between the summit and toe slope positions should be minimal. This hypothesis was confirmed through analysis that is detailed on page 65. To further minimize variability, all sample sites were located in open areas, away from the break in slope, on north-facing slopes ranging from zero to five percent.

Table 4.1

Summary of Site Characteristics

Site	Slope Position	Slope Angle	Aspect	Map Unit	Texture
NORTHERN REGION					
NNTA	Summit	< 5%	North	Siweeka	Sandy loam
NCTA	Toe	< 5%	North	Siweeka	Sandy loam
NNTF	Toe	< 5%	North	Siweeka	Sandy loam
NCTF	Summit	< 5%	North	Siweeka	Sandy loam
NCRP	Toe	< 5%	North	Siweeka	Sandy loam
CENTRAL REGION					
CNTA	Summit	< 5%	North	Touhey	Sandy loam
CCTA	Toe	< 5%	North	Touhey	Sandy loam
CNTF	Summit	< 5%	North	Touhey	Sandy loam
CCTF	Toe	< 5%	North	Touhey	Sandy loam
CCRP	Toe	< 5%	North	Touhey	Sandy loam
SOUTHERN REGION					
SNTA	Toe	< 5%	North	Touhey	Sandy loam
SCTA	Summit	< 5%	North	Touhey	Sandy loam
SNTF	Toe	< 5%	North	Touhey	Sandy loam
SCTF	Toe	< 5%	North	Touhey	Sandy loam
SCRP	Summit	< 5%	North	Touhey	Sandy loam

Sample Site Descriptions

Northern Region

The Northern Region, located northeast of Mold, extended nearly 1.5 miles north-south, and just over 0.5 miles east-west. The soil type at each of the five sample sites was

Siweeka, map unit 327, Figure 4.2. The rain gauge for the Northern region was located at N 47° 46.400’, W 119° 17.839’ at 705 m elevation (Figure 4.3).

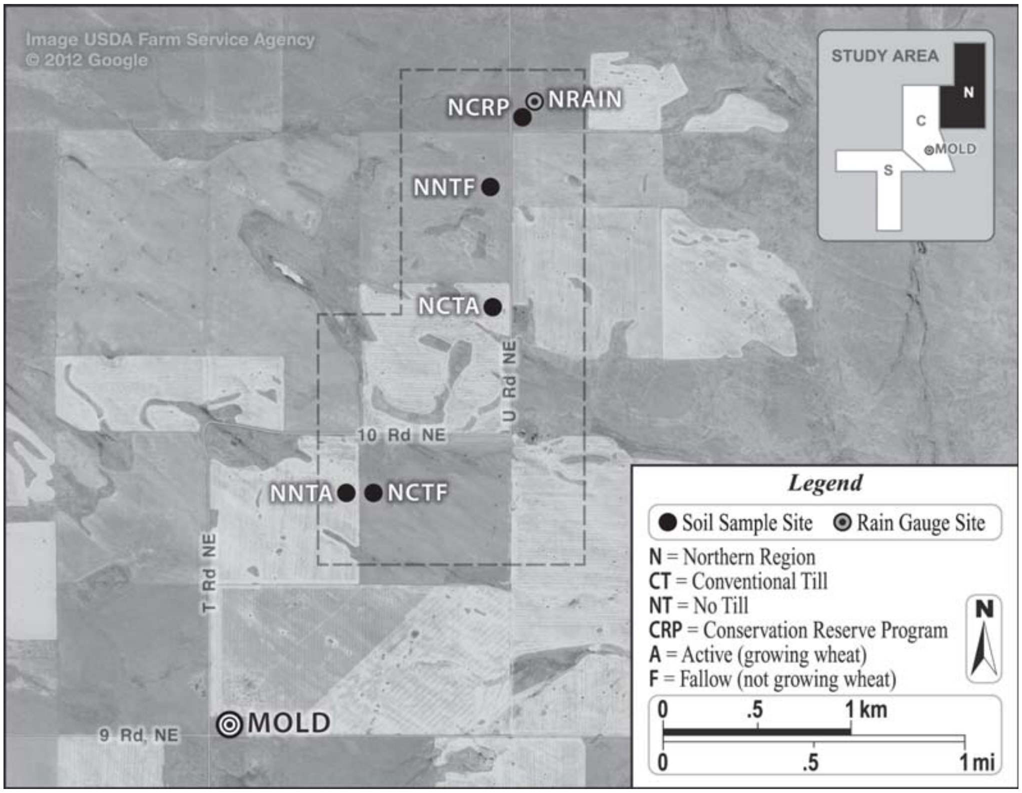

Figure 4.3. Northern region sample sites and rain gauge location.

NNTA (Figure 4.4) – (NE ¼ S16, T26, R28, WM). The site was actively growing wheat at N 47° 45.306’, W 119° 18.603’ at 711 m elevation. The site was located in the summit slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was Eltan$^{©}$ wheat (*Triticum aestivum*). Cheat grass (*Bromus tectorum),* and mustards (*Brassica spp*.) grew around the field’s perimeter.

NCTA (Figure 4.5) – (SE ¼ ,S9, T26, R28, WM). The site was actively growing wheat at N 47° 45.818’, W 119° 17.992’ at 705 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was Eltan© wheat (*Triticum aestivum*). Cheat grass (*Bromus tectorum)*, and mustards (*Brassica spp*.) grew around the field's perimeter.

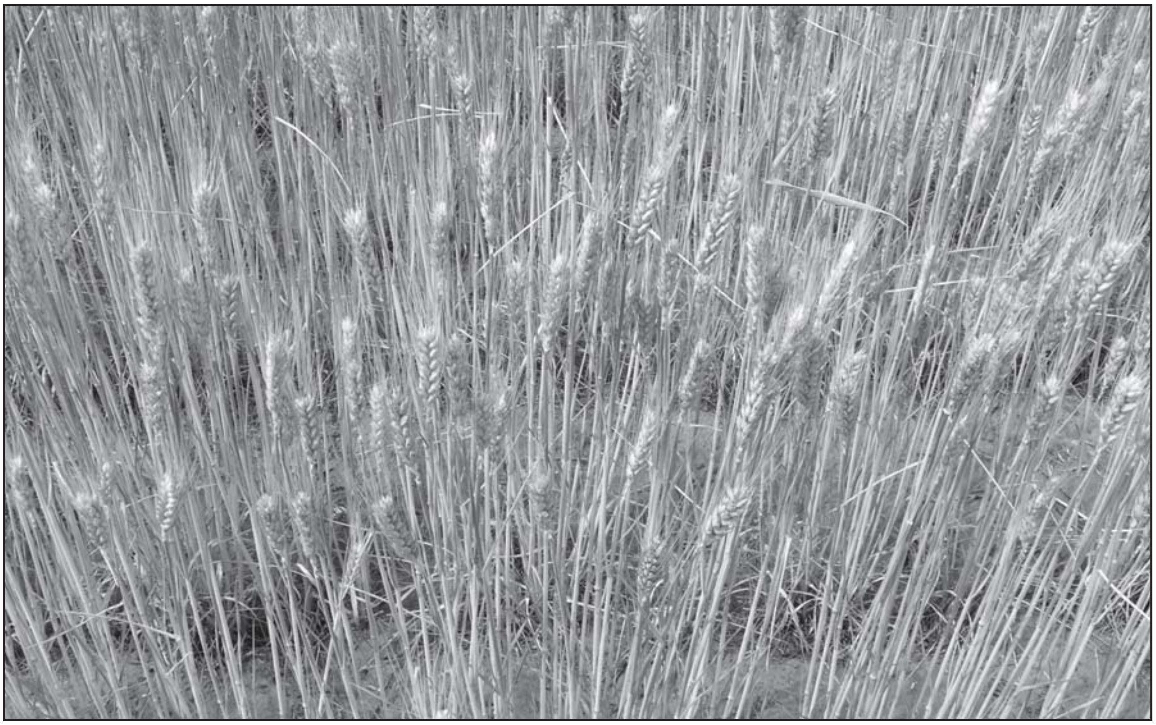

Figure 4.4. Northern region NTA site, full-headed wheat. 7/24/11.

Figure 4.5. Northern region CTA site, view to the west. 7/10/11.

NNTF (Figure 4.6) – (NE ¼, S9, T26, R28, WM). The site was in fallow, located at N 47° 46.164,' W 119° 18.001' at 721 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was wheat stubble (*Triticum aestivum*), cheat grass (*Bromus tectorum)*, dalmatian toadflax (*Linaria dalmatica*), and mustards (*Brassica spp*.) such as Jim Hill mustard (*Sisymbrium altissimum)*.

Figure 4.6. Northern region NTF site, view to the northwest. 8/7/11.

NCTF (Figure 4.7) – (NW ¼ S15, T26, R28, WM). The site was in fallow, located at N 47° 45.268,' W 119° 18.471' at 714 m elevation. The site was located in the summit slope position with a slope angle of less than 5%, and a north aspect. No vegetation grew.

NCRP (Figure 4.8) – (SW ¼ ,S3, T26, R28, WM). The site was located at N 47° 46.344', W 119° 17.879' at 704 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was primarily bluebunch wheatgrass (*Pseudoroegneria spicata*), cheat grass (*Bromus tectorum)*, Idaho fescue (*Festuca idahoensis)*, big sagebrush (*Artemisia tridentata*) and three-tip sagebrush (*Artemisia tripartita*). Wildflowers, such as larkspur (*Delphinium staphisagria)*, lupine *(Lupinus spp.)*, and goldenrod (*Solidago spp.),* also grew there.

Figure 4.7. Northern region CTF site, the rockiest of the CT fields, view to the southwest. 6/7/11.

Figure 4.8. Northern region CRP site, view to the east. 4/23/11.

Central Region

Mold is located on the southern edge of the central region. The central region's northernmost sample site was .5 miles west, northwest of the northern region's southernmost site (Figure 4.9). The sites were distributed over a distance of 1.5 miles south and less than a half mile east. The soil type for each sample site was Touhey, map unit 426, Figure 4.2. The central rain gauge was positioned at N 47° 45.515', W 119° 19.227' at 696 m elevation. Located at the McDonald farmhouse was the Watchdog® weather station, just over one half mile east of the region's southernmost sample site.

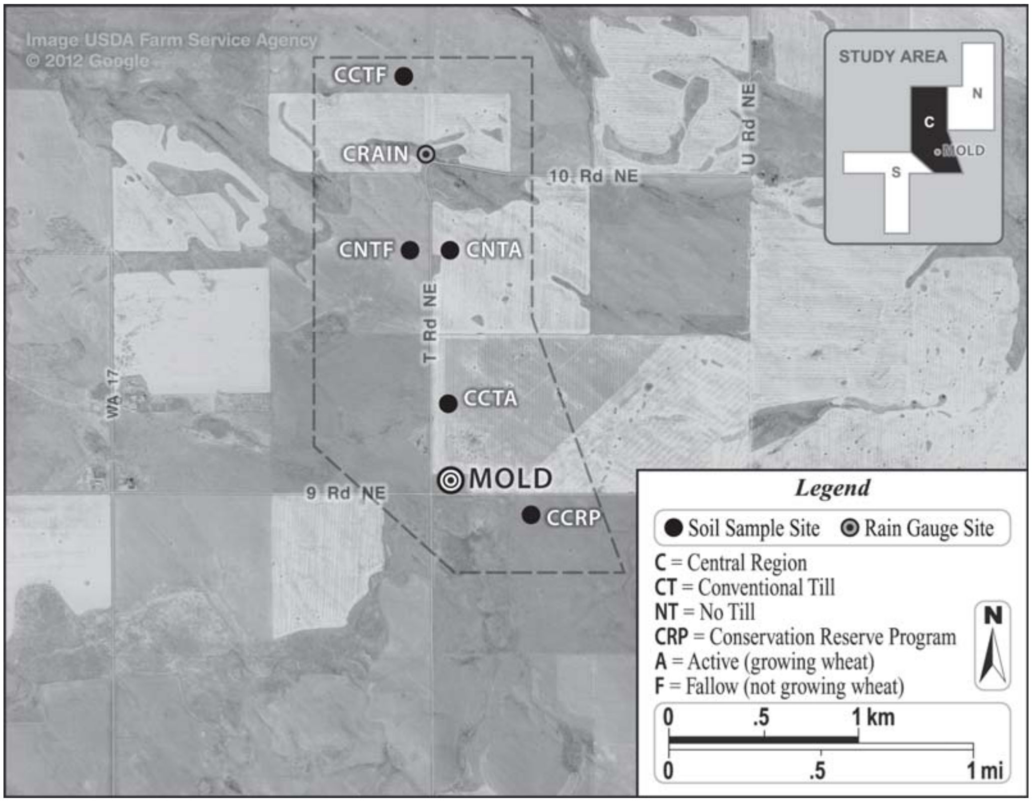

Figure 4.9. Central region sample sites and rain gauge locations. Farmhouse is also the location of the Watchdog® weather station.

CNTA (Figure 4.10) – (NW ¼ S17, T26, R28, WM). The site was actively growing wheat at N 47° 45.259', W 119° 19.295' at 720 m elevation. The site was located in the summit slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was Eltan© wheat (*Triticum aestivum*). Cheat grass (*Bromus tectorum)*, and mustards (*Brassica spp*.) grew in abundance around the field's edges.

Figure 4.10. Central region NTA, with full-headed wheat near harvest time, view to the east. 8/21/11.

CCTA (Figure 4.11) – (SW ¼ S16, T26, R28, WM). The site was actively growing wheat at N 47° 44.838', W 119° 19.154' at 709 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was Eltan© wheat (*Triticum aestivum*). Cheat grass (*Bromus tectorum)*, and mustards (*Brassica spp*.) grew along the edges of the field.

CNTF (Figure 4.12)– (NE ¼ S16, T26, R28, WM). The site was in fallow at N 47° 45.255,' W 119° 19.158' at 716 m elevation. The site was located in the summit slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was wheat stubble (*Triticum aestivum*), cheat grass (*Bromus tectorum)*, dalmatian toadflax (*Linaria dalmatica*), and mustards (*Brassica spp.*) such as Jim Hill mustard (*Sisymbrium altissimum)*.

Figure 4.11. Central region CTA, mid-spring, view to the northeast. 5/7/11.

Figure 4.12. Central region NTF, view to the west. 4/3/11.

Figure 4.13. Central region CTF, dust mulch. 8/7/11.

CCTF (Figure 4.13)– (SE ¼ S8, T26, R28, WM). The site was in fallow at N 47° 45.690,’ W 119° 19.298’ at 702 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. No vegetative cover grew here.

CCRP (Figure 4.14) – (NW ¼ S21, T26, R28, WM). The site was located at N 47° 44.536’, W 119° 18.821’ at 710 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. Lupine *(Lupinus spp.)* and bitterbrush (*Purshia tridentata*) were abundant. Goldenrod (*Solidago spp.),* big sagebrush (*Artemisia tridentata*) and three-tip sagebrush (*Artemisia tripartita*) grew sporadically.

Figure 4.14. Central region CRP, view to the southeast. 4/3/11.

Southern Region

The southern region extended nearly 1.5 miles west from the central region, with one sample site located almost one mile to the south (Figure 4.15). Mold is located at the northern edge of the southern region. The soil type for each sample site was Touhey, map unit 426, Figure 4.2. The southern rain gauge was positioned at N 47° 43.26’, W 119° 20.219’ at 715 m elevation.

SNTA (Figure 4.16) – (NE ¼ S19, T26, R28, WM). The site was actively growing wheat at N 47° 44.540’, W 119° 20.679’ at 697 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was Eltan© wheat (*Triticum aestivum*). Cheat grass (*Bromus tectorum)*, and mustards (*Brassica spp*.) grew extensively around the field’s edges.

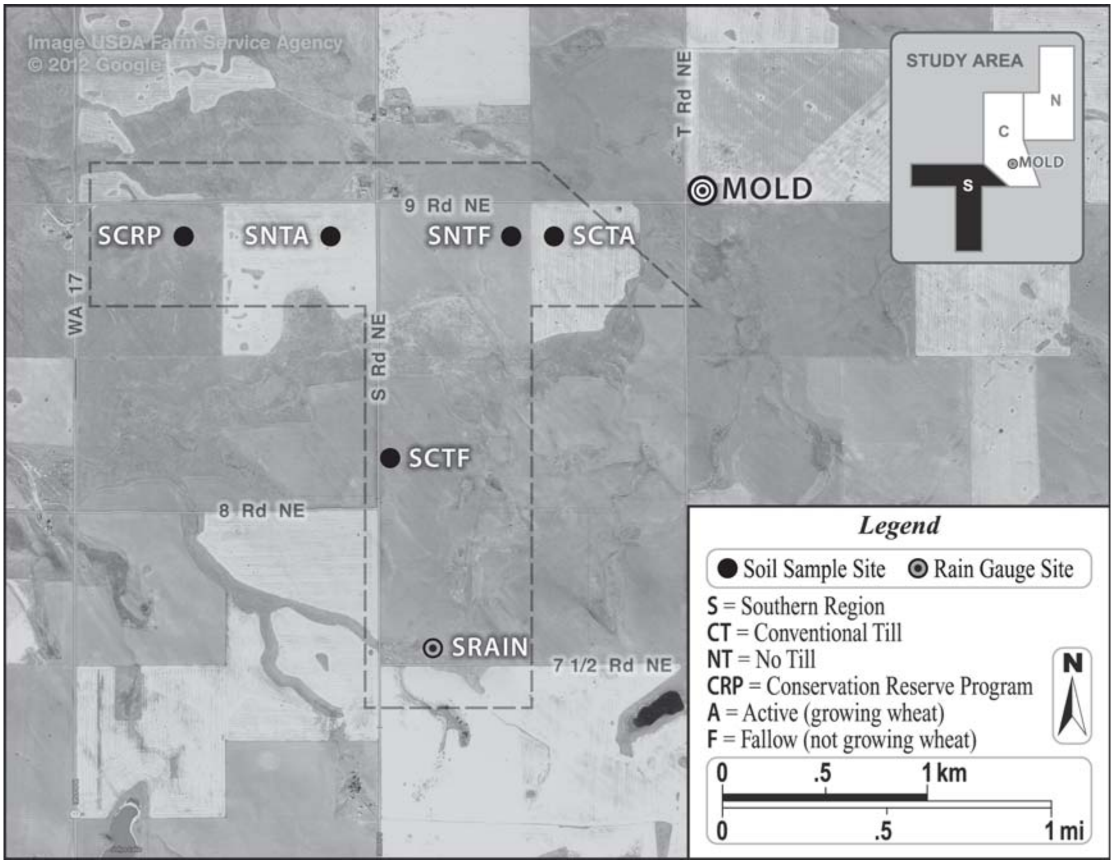

Figure 4.15. Southern region sample sites and rain gauge location.

Figure 4.16. Southern region NTA. 8/21/11.

SCTA (Figure 4.17) – (NE ¼ S20, T26, R28, WM). The site was actively growing wheat at N 47° 44.519’, W 119° 19.815’ at 713 m elevation. The site was located in the summit slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was Eltan© wheat (*Triticum aestivum*). Cheat grass (*Bromus tectorum)*, and mustards (*Brassica spp*.) grew around the field’s edges.

Figure 4.17. Southern region CTA site. 5/22/11.

SNTF (Figure 4.18) – (NW ¼ S20, T26, R28, WM). The site was in fallow at N 47° 44.511,' W 119° 19.899' at 700 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was wheat stubble (*Triticum aestivum*), cheat grass (*Bromus tectorum)*, dalmatian toadflax (*Linaria dalmatica*), and mustards (*Brassica spp*.) such as Jim Hill mustard (*Sisymbrium altissimum)*.

SCTF (Figure 4.19) – (NW ¼ S29, T26 R28, WM). The site was in fallow at N 47° 43.881' W 119° 20.434' at 706 m elevation. The site was located in the toe slope position with a slope angle of less than 5%, and a north aspect. No vegetative cover existed here.

Figure 4.18. Southern region NTF, used for grazing following harvest, view to the east. 10/23/11.

SCRP (Figure 4.20) – (NW ¼ S19, T26, R28, WM). The site was located at N 47° 44.496’, W 119° 21.299’ at 698 m elevation. The site was located in the summit slope position with a slope angle of less than 5%, and a north aspect. The vegetative cover was primarily bluebunch wheatgrass (*Pseudoroegneria spicata*), Sandberg bluegrass (*Poa secunda*), cheat grass (*Bromus tectorum),* and Idaho fescue (*Festuca idahoensis)*. Lupine *(Lupinus spp.)* and bitterbrush (*Purshia tridentata*) were abundant. Goldenrod (*Solidago spp.),* big sagebrush (*Artemisia tridentata*) and three-tip sagebrush (*Artemisia tripartita*) grew sporadically.

Figure 4.19. Southern region CTF, tilled, not yet dust mulch, view to the north. 4/23/11.

Figure 4.20. Southern region CRP, view to the north. 6/21/11.

Topography

Sample sites were selected based on similarities of slope and aspect. A standard slope angle and aspect for each sample site in the study area was determined using topographic maps, airphotos, ground truthing with a clinometer, and the Dalrymple, Blong, and Conacher (1968) slope profile. Each sample site was located on the summit or toe slope position, of a slope ranging from 0 to 5% with a north aspect.

As previously mentioned, it was hypothesized that since slope segments on the same soil map unit should have the same infiltration rate, and precipitation was low in the study area, moisture differences between the summit and toe slope positions should be minimal.

Soil Texture

The Douglas County Soil Survey was used to determine the expected soil texture for each sample set. The soil texture was documented for one sample at each sample site using the hydrometer method, in which texture is determined by the settling rate of soil particles in solution (Gee & Bauder, 1986; NRCS, 2008). Documentation was performed at the Central Washington University Geomorphology and Soils Lab in September 2010. The hydrometer method confirmed the fine sandy loam designation of the soil survey for all sample sites.

Two soils were selected for the study: Siweeka complex (soil map unit 428), 0 to 8% slopes and Touhey complex (soil map unit 327), 0 to 8% slopes (NRCS, 2008). These soils are identical in composition, structure and texture with the primary difference being that the Touhey complex receives less precipitation than the Siweeka complex

(USDA/NRCS, 2011). Touhey is reported to receive 25.4 cm of precipitation and has an annual air temperature of 9.4 C° where it is found, while Siweeka receives 35.56 cm of precipitation and has an annual air temperature of 8.9 C° It should also be noted that in the Range of Characteristics section of the soil description for Touhey (Appendix B) it states that the mean annual soil temperature is between 10 C° and 11.7 C° while the same section in the Siweeka (Appendix A) soil description states that the mean annual soil temperature is between 9.4 C° and 10.5 C°. Also of note is the difference in description of the soil moisture control sections of these two soils. The moisture control section in Touhey is described as dry for one-half to three quarters of the time when the soil temperature is above 5 C°. Conversely, Siweeka is described as moist in the moisture control section, but dry for 90 to 105 consecutive days after summer solstice. Two soil scientists with the Natural Resources Conservation Service, Chuck Natsuhara and Chandra Neils, were consulted and confirmed that these soils are similar enough to be compared in the study.

Land Use

Land use is defined for the purpose of this study as CT, NT, and CRP. CT is the traditional method of farming for the area. It is characterized by the significant amount of soil disturbance and incorporation of crop residues into the soil. Two CT land use types were used for this study: conventional tillage active (CTA), and conventional tillage fallow (CTF). CTA plots were actively growing a wheat crop, while CTF fields were in fallow and not growing a wheat crop until the following year.

NT is defined as minimal to no surface disturbance, in which the residues from the previous crop are left standing and form a layer of organics at the soil surface. Two NT land use types were used for this study: no tillage active (NTA), no tillage fallow (NTF). NTA plots were actively growing a wheat crop, while NTF fields were in fallow and not growing a wheat crop until the following year.

CRP is defined as land under contract with the Farm Service Agency that is currently not being farmed. Under contract, these lands were removed from crop production and planted to annual and perennial grasses and native vegetation. These areas tend to emulate natural pre-settlement conditions. CRP fields were chosen as a control group to approximate natural conditions and give a baseline for comparative analysis.

Soil Moisture Measurement

Many methods may be used to determine soil moisture. Two of these methods, gravimetric and Time Domain Reflectometry (TDR), were used in this study. Gravimetric procedures measure the mass of water in a given soil sample, while TDR measures the volume of water. For reasons explained later, only TDR samples were used in analysis. Soil moisture was measured approximately every two weeks. Sample dates are detailed in Table 4.2.

Table 4.2.

Sample Dates and Procedures.

Sample Date	10/23/10	11/4/10	11/19/10	3/6/11	4/3/11	4/23/11	5/7/11	5/22/11	6/7/11	6/21/11	7/10/11	7/24/11	8/7/11	8/21/11	9/16/11
Procedure															
Gravimetric	x	x	x		x	x	x	x	x	x	x	x	x	x	x
TDR	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Precipitation Gauge	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Precipitation Watchdog®	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Temperature	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Evaporation	x	x	x				x	x	x	x	x	x	x	x	x

TDR Procedures

A Field Scout® portable handheld TDR probe (Model # 200) was used in this study. The probe consisted of a handle that contained the electronics and two 20 cm parallel stainless steel rods mounted 3.3 cm apart in the handle unit. TDR measures the soil water content *in situ* using a probe that emits an electromagnetic pulse. The parallel rods of the unit receive the pulse, measure the velocity and translate it to the volumetric water content (VWC) in the soil sample (Maroufpoor et al., 2009, Topp & Davis, 1984). The VWC is the ratio of the volume of water in a soil to the total soil volume (Topp & Davis, 1984).

The average planting depth for winter wheat by the farmers in the study area is 15 cm, therefore it was chosen as the sample depth. TDR samples were taken at 15 cm depth using the hand held TDR probe at each of the 15 sample sites. At each of the sample sites, the probe was inserted into the soil three times within a 1 ft^2 area. Soil moisture readings were expressed in percent of moisture in the soil to the nearest tenth of a percent. After the percentage of water in the soil was recorded, the TDR probe was carefully removed and a gravimetric sample was taken from between the holes made by the rods of the TDR probe (Topp & Davis, 1984).

TDR has been shown to be a fast, reliable method for measuring the volumetric water content of a soil (Benson & Bosscher, 1999; Noborio, 2001; Rajkai, & Ryden, 1992). The volumetric water content of a soil is the volume of water compared to the total volume of soil (Benson, & Bosscher, 1999; Noborio, 2001). The gravimetric water content is the mass of water compared to the mass of dry soil solids (Strangeways, 1999; Yu & Drnevich, 2004). While gravimetric water content is related to volumetric water content, the two methods of moisture measurement reflect different aspects of the areal distribution of moisture in the soil (Yu & Drnevich, 2004). Volume and mass can be converted to each other for comparison if the bulk density is known (Rajkai & Ryden 1992).

TDR has been shown to be highly reliable in field applications, providing an instant reading of water content and reducing the amount of error inherent in other forms of soil water measurement (Topp & Davis, 1984; Walker, Willgoose, & Kalma, 2004). Studies have shown that the values determined through TDR are as accurate as the values from gravimetric samples (Rajkai & Ryden, 1992; Topp & Davis, 1984). Rajkai and Ryden (1992) found that the error associated with moisture measurement was reduced when the number of samples were increased. They found error was reduced to +/- .5% when they took 13 TDR measurements. Seven was the corresponding number in gravimetric samples. They point out that if 1% is accepted for random error, only two gravimetric and three TDR samples are needed.

Advantages of TDR over other methods, including gravimetric, is its ability to rapidly measure both electrical conductivity and soil water content with the same probes and in the same sampling volume (Wraith, Robinson, Jones, & Long, 2005). Additionally, TDR is well suited to near-surface measurements because it gives instant results, can make a large number of field measurements in a day, takes non-destructive samples, and often does not require soil-specific calibration (Rajkai & Ryden, 1992; Topp & Davis, 1984; Wraith et al., 2005).

Disadvantages of the TDR method are the cost of equipment (ranging from $700 to $1,100 per unit) and decreased wavelength response in highly saline soils (Strangeways, 2003; Topp & Davis, 1984). Wraith et al. (2005) also found that TDR is not well suited to very hard or stony soils, which can prevent insertion or create air voids adjacent to the rods that contribute to inaccurate measurements. Errors due to rod displacement in stony soils can be corrected with the use of an inexpensive flexible connector as described in Souto, Defonte, and Escariz (2008) that reduces air gaps and compression zones.

Gravimetric Procedures

An AMS 7/8″ x 33″ open-end soil probe (Model #401.21) was used to collect soil samples. Samples of 2.54 cm in diameter were taken to a 15 cm depth with the hand-held soil probe at each of the fifteen sample sites. One gravimetric sample was taken at each sample site per visit. Samples were emptied from the probe directly into Ziploc® bags using a wooden dowel to push the sample out of the probe. Samples were then double bagged in Ziploc® bags and placed in an ice chest for transport from the field back to the CWU Geomorphology & Soils Lab.

Upon arrival at the lab, all samples were placed in soil tins and weighed using a Ohaus Scout® Pro digital scale. These values were recorded to the nearest hundredth of a gram. Samples were then placed in an oven set at 105 °C and left to dry for 24 hours. After all the gravitational and capillary water was removed, samples were reweighed using the same scale and the values were recorded. The difference in the wet weight vs. dry weight was the soil water content in grams (Maroufpoor et al., 2009; Schillinger et al., 2007).

Disadvantages associated with the gravimetric method include: the need for sample removal from the site; the time delay between sample removal and oven drying; the potential for error during sampling and processing (Topp & Davis, 1984).

Gravimetric Sampling Error

Both TDR and gravimetric soil moisture values were gathered at each sample site throughout the year. After analysis it was determined that the gravimetric data had significant errors due to inconsistent depth of sampling. Once soil moisture decreased below approximately 15%, as measured by TDR, the ground was too hard to allow a consistent sampling to 15 cm depth.

While many studies indicate that gravimetric and TDR can be used interchangeably, these studies were not done in Eastern Washington, an area of hard, often dry soils, for a large portion of the year. Therefore, gravimetric data was not used for analysis. TDR provided the data for this study's analysis because TDR samples consistently reached 15 cm depth.

Different sampling equipment that is better suited to working in the dry soil conditions of Eastern Washington is suggested for future studies. If a TDR probe was not available, gravimetric sampling could be done instead, by excavating to depth with a small shovel or trowel. For this study, TDR was found to be more suitable for the conditions than gravimetric handheld probe sampling.

Soil Moisture/Land Use Statistical Analysis

TDR soil moisture values were statistically analyzed using non-parametric tests with the Statistix® computer program. Non-parametric statistical tests were chosen for data analysis, due to small sample sizes, and the fact that data did not have a normal (bell-shaped) distribution and did not satisfy the other assumptions required for parametric tests (Siegel, 1957). Soil moisture data was analyzed by land use, both regionally and individually using the Kruskal-Wallis, Wilcoxon Rank Sum and Wilcoxon matched pairs tests (Wilcoxon, 1945). Soil moisture was then analyzed in relation to precipitation, temperature, and evapotranspiration with consideration for land use type using the Spearman rank correlation (Siegel, 1957).

Precipitation Measurement

The most common method for measuring precipitation is with a rain gauge. Rain gauges are accurate, inexpensive and easy to use (Rodda, 1967). While gauges have been found to provide highly accurate data for a specific location, the temporal and spatial variation of precipitation poses a problem to accurate data collection when few gauges are used to cover a larger study area (Villarini, Mandapaka, Krajewski, & Moor, 2008). Additionally, variations in the duration and intensity of the rain event, the effects of wind and evaporative losses can increase error in rainfall estimates (Rodda, 1967). Potential for error also increases as the size of the collector opening decreases, and when the gauge is not level (Strangeways, 2003).

Precipitation that falls as snow can be equally difficult to measure. The most common method is measuring snow depth after the snow has fallen. The snow depth, combined with its density, can be used to determine snow water equivalent (Marks, Mcgurk & Berg, 1988). The presence of wind can cause problems with the accuracy of snow depth measurements as it can move snow around, increasing and decreasing snow depth over the study area (Rodda, 1967). Due to the inaccessibility of the site during the winter months, snow depth was not measured.

Four All Weather® rain gauges were placed in the study area, one in each of the three sections and one at the farmhouse next to the Watchdog® weather station. The All Weather® rain gauge is composed of a larger outer tube, surrounding a smaller inner measuring tube topped by a funnel. The outer tube measures 35.5 cm x 12.7 cm, while the inner tube measures 35.5 cm x 5 cm. The top of the funnel collects the rain and channels it into the smaller measuring tube that has a total capacity of 25.4 mm and is graduated every 2 mm.

Due to highly variable precipitation patterns in dryland environments (Laity, 2008), rain gauge placement was designed to achieve the best coverage of the study area. The gauges were mounted on T-posts at the height of 5 ft and leveled with a bubble level to that height after every data collection. Gauges were placed in the open away from rock piles and buildings and were surrounded with chicken wire fencing anchored by posts to keep wildlife disturbance to a minimum. Readings were taken directly from the measuring tube. These readings were recorded in a field notebook and the data was later entered into an Excel® file containing all sample data. Once data collection was complete, these data were imported into Statistix® and analyzed using non-parametric tests.

During the winter months when the study area was inaccessible, the top funnel and inner measuring tubes were removed from the gauges in order to collect snow. The outer tube was filled with 20 mm of "environmentally-safe" antifreeze to protect against freezing and to melt snow as it fell into the tube for snowfall water content estimation. The gauges were not checked from November 20, 2010 to March 6, 2011 when the area again became accessible. During that time, precipitation had accumulated in the outer tube, and was not overflowing. On March 6, the tubes were removed from the posts and the contents were measured using the smaller inner tube. The first 20 mm were discarded due to the addition of 20 mm of antifreeze. The remaining water was then measured by filling the tube, taking a reading, discarding the water and repeating until all the water had been measured. The final measurement consisted of holding the outer tube upside down over the inner tube for 25 seconds and until dripping had stopped. The data was then recorded in a field notebook. The outer tubes were then refilled with 20 mm of antifreeze until April 23, when the threat of freezing had passed. At that time, the top funnel and inner tube were replaced on the rain gauge.

A Watchdog® 2000 Series recording weather station (Model # 2475) was set up in the center section of the study area at the Farmhouse. It digitally recorded climate continuously for the duration of the study. Precipitation was measured using a tipping bucket rain collector (Model # 3665R) at 5-minute intervals every day. The bucket measured rainfall in 0.00254 cm increments and was self-emptying. This weather station was used to collect an accurate record of climate in the Farmhouse area and to check the accuracy of the other precipitation data collection points in the study. Data from this weather station were retrieved on average once every 2 weeks, except in the winter months when the area was inaccessible. Once the area was again accessible, data from the winter months were retrieved, downloaded, and recorded.

Soil Moisture/Precipitation Statistical Analysis

The relationship between soil moisture and precipitation was statistically analyzed using the Spearman rank correlation test with the Statistix® computer program with the significance level set at $p < 0.05$. Precipitation data from 14 days prior to each soil moisture sample date was compared to the soil moisture sample values. The null hypothesis was that no significant relationship existed between precipitation and soil moisture. The alternative hypothesis was that a significant relation did exist.

Temperature Measurement

The Watchdog® weather station digitally recorded air temperature at 30-second intervals every day. Data from this weather station were retrieved on average once every two weeks, except in the winter months when the area was inaccessible. Once the area was again accessible, data from the winter months were retrieved, downloaded, and recorded. The collected temperatures were compared to soil moisture values throughout the study area.

Soil Moisture/Temperature Statistical Analysis

The relationship between soil moisture and temperature was statistically analyzed using the Spearman rank correlation test with the Statistix® computer program with the significance level set at $p < 0.05$. Temperature data from 14 days prior to each soil moisture sample date was compared to the soil moisture sample values. The null hypothesis was that no significant relationship between temperature and soil moisture existed. The alternative hypothesis was that a significant relation did exist.

Evaporation Measurement

Evaporation is shaped by the factors of temperature, sunshine, humidity, soil moisture availability, and wind. The standard method of measuring evaporation is the use of a “Class A” evaporation pan. These pans are made of stainless steel and are 54 mm high and 206 mm in diameter. The pan is put on a wooden support in an open area on level ground (Brouwer & Heibloem, 1986).

Due to the prohibitive cost of purchasing “Class A” evaporation pans for the study, low cost evaporation pans were constructed following the directions of Mancuso (2005). Four pans were constructed and placed adjacent to each precipitation gauge. Evaporation pans and precipitation gauges were surrounded with chicken wire fencing anchored by posts to keep wildlife disturbance to a minimum. Evaporation pans were elevated off the ground on cement blocks. Blocks were hand leveled using a bubble level prior to placement, and leveled each time the pans were moved. Pans were filled with water to within a ¼ inch of the top. The initial water level reading was taken by reading the water level in the tube in relation to the measuring tape glued to the side of the pan. After each data reading was recorded, water was refilled to the original level as needed.

Evaporation data were collected using these small homemade evaporation pans from October 23, 2010 to September 16, 2011 (Table 4.3). Evaporation pan data were not collected during the winter months. The pans were removed on November 19, 2010, when freezing temperatures rendered them useless. They were reinstalled at each site on April 23, 2011 after the threat of freezing had passed. By the first sample date 2 weeks later, the pans proved to be too shallow for consistent, reliable readings. Because the pans were empty each time they were subsequently checked, a minimum evaporation amount is all that is known for certain. At least 10 cm of water had evaporated between sample days, but the actual evaporation amount could be much more. This data was not accurate enough for statistical analysis in relation to soil moisture.

Table 4.3.

Evaporation Pan Data in Centimeters

Region	10/23/2010	11/4/2010	11/19/2010	5/7/2011	5/22/2011	6/7/2011	6/21/2011	7/10/2011	7/24/2011	8/7/2011	8/21/2011	9/16/2011
Northern	0.8	1.5	0	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10
Central	1.3	2	0	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10
Southern	0.6	0.8	0	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10
Farmhouse	0.9	0.5	0	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10	≥10

Note. Evaporation in centimeters. ≥10 is determined due to empty pan on sample date. The 0 reading on 11/19/11 was due to the water in the pan being frozen.

Homemade evaporation pans provided only a base minimum evaporation data set, so supplemental data was needed. These data were obtained from the nearest weather station to the study area. The St. Andrews weather station is located approximately 7.9 km from the center of the study area (Figure 3.1) and gathers evapotranspiration data for grass and alfalfa. Grass evapotranspiration data was used in the analysis. Evapotranspiration includes not only evaporation values, but also wind, and plant transpiration in removing moisture from the soil and is often used in these analyses due to the difficulty of separating the two processes (Strangeways, 2003).

Soil Moisture/Evaporation Statistical Analysis

To ensure that the evapotranspiration data retrieved from the St. Andrews weather station was comparable to evaporation at the study area, a Spearman rank correlation ($p < 0.05$) was run using temperature data from the St. Andrews site and the Watchdog® weather station for the same dates (April 1 to April 16, 2011). This test was chosen to determine the strength of the link between the two sets of data. The null hypothesis was that there was no significant relationship between temperature data from the Watchdog® and the St. Andrews weather site. The alternative hypothesis was that a significant relation did exist. A Wilcoxon signed rank test was then run to determine if there were differences between the two data sets.

Once the evapotranspiration data from St. Andrews was determined to be comparable, data from 14 days prior to each soil moisture sample date was compared to the soil moisture sample values using Spearman rank correlation and Wilcoxon signed rank using the Statistix® computer program ($p < 0.05$).

CHAPTER V

RESULTS AND DISCUSSION

General Trends in Soil Moisture

Data collection began in October 2010, but data analysis was performed only on data gathered between April 3, 2011 and September 16, 2011. Starting in November, 2010, the study area was inaccessible due to heavy snow and impassible roads. At that point, only three sample days of data had been gathered. While the Watchdog® collected data continuously throughout the study, soil moisture data was not collected during the winter. The winter precipitation gathered by the All Weather® rain gauges was measured only once, in March. Because data from spring thaw to late-summer harvest was consistently obtained, it was chosen for statistical analysis.

Data shows that the soils in all fields, in all 15 sample sites of the three regions (N, C, S) of the study area gained moisture throughout the fall and winter, reaching maximum moisture over the winter. Moisture values fluctuated throughout the spring and into summer. Soil moisture went in a steady decline from the beginning of June until the end of the study as precipitation events decreased and evapotranspiration increased. Soil moisture differences were found between regions and by treatment. These are discussed below, followed by in-depth statistical analysis of moisture values in relation to the variables examined.

CRP Comparison

CRP fields in all regions had established grassland cover. CRP fields were chosen as a control group approximating natural conditions and used as a basis for comparison to the other land use types in the study. Prior to comparison to other land uses, CRP fields were compared to each other (Figure 5.1). Initial soil moisture values for each region after the soil had thawed were similar, ranging from 21% to 23%. While moisture values dropped steadily throughout the spring into the fall, the Northern region consistently held more soil moisture than the Central and Southern regions, by more than 5% for the majority of the time. The Northern region had 4% moisture at the end of the study, compared to 2% in the Southern region and 1% in the Central region. Moisture losses are likely due to a combination of evaporation and plant transpiration.

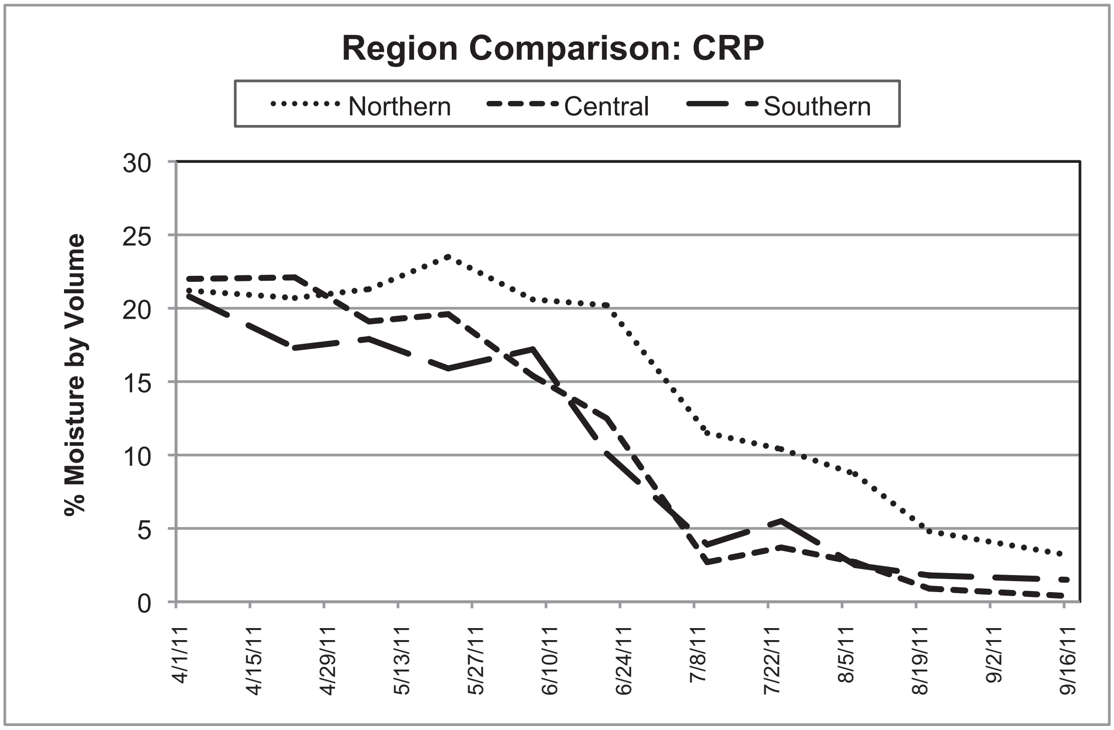

Figure 5.1. Regional comparison of CRP soil moisture values.

Active Field/CRP Comparisons

Fields that were actively growing wheat under CT and NT were compared to fields enrolled in CRP. CRP fields were chosen as a control group approximating natural conditions and compared to the wheat fields of CT and NT. Soil moisture values were analyzed from April 3, 2011, when the soil had thawed, to September 16, 2011, after harvest of the crop.

Northern Region

A comparison of soil moisture values for the Northern region (Figure 5.2) shows that on April 3, 2011 the CT field was 26% moisture by volume in the sample, while on the same date the NT field contained 21% soil moisture by volume. The CRP field also had 21% soil moisture by volume at this time. As time passed, CRP values remained 4 to 7% higher than both CT and NT fields. Also, CT and NT values were relatively similar except on June 7, 2011 when CT was higher than NT. At the end of the study, the final moisture value for CT and NT was 0% moisture. This final value was taken at the end of the growing season and the dry season, after harvest when the wheat had exhausted soil moisture supplies, when only hygroscopic water remained in the soil. Conversely, the Northern CRP field soil moisture value was 4%. The higher percentage could be due to having vegetative cover that is adapted to living under water stress, as well as having enough cover that can be supported by soil moisture in the area (NRCS, 2008). Crops, by contrast, are artificially grown in the area. While cereal crops are often successful in dry environments, the natural vegetation is still better adapted to the aridity (Mahdi et al., 1998; Shunqing et al., 2003).

An additional explanation could be that CRP fields might have a higher percent of macropores than actively cultivated fields (Johnson & Quarles, 1998). Tillage operations have not occurred on CRP fields for 10 to 15 years, or more (FSA, 2012). As a result, animal burrows, and plant roots have created macropores within the soil that remain from year to year without disturbance (Johnson & Quarles, 1998; Karlen et al., 1998). These macropores create additional space for precipitation to infiltrate, increasing the water-holding capacity of the soil.

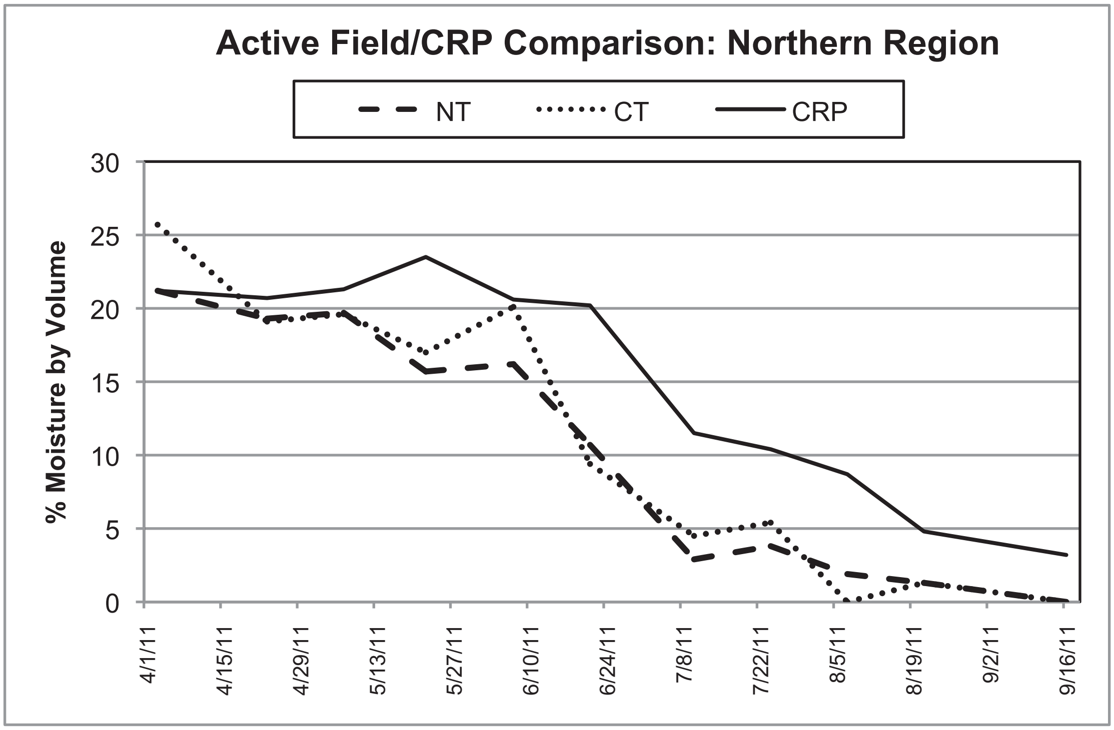

Figure 5.2. Active comparison: Northern region

Central Region

In the Central region (Figure 5.3), NT soil moisture values started out higher than CT values after the thaw. The NT field initially had a moisture value of 25% moisture by volume, compared to the 22% soil moisture of the CRP field and the 20% moisture of the CT field. Unlike the Northern region, the NT field clearly held more moisture well into the summer, after which, it dropped to similar levels for the remainder of the study. NT values were higher than the CRP moisture values until the end of June. The additional moisture provided by NT in the active field of the Central area could have only been beneficial to plant growth as the weather got progressively hotter and drier. CRP soil moisture values remained 1 to 3% higher than both NT and CT from the end of June through the end of the study. The same factors discussed in the Northern section likely explain the differences.

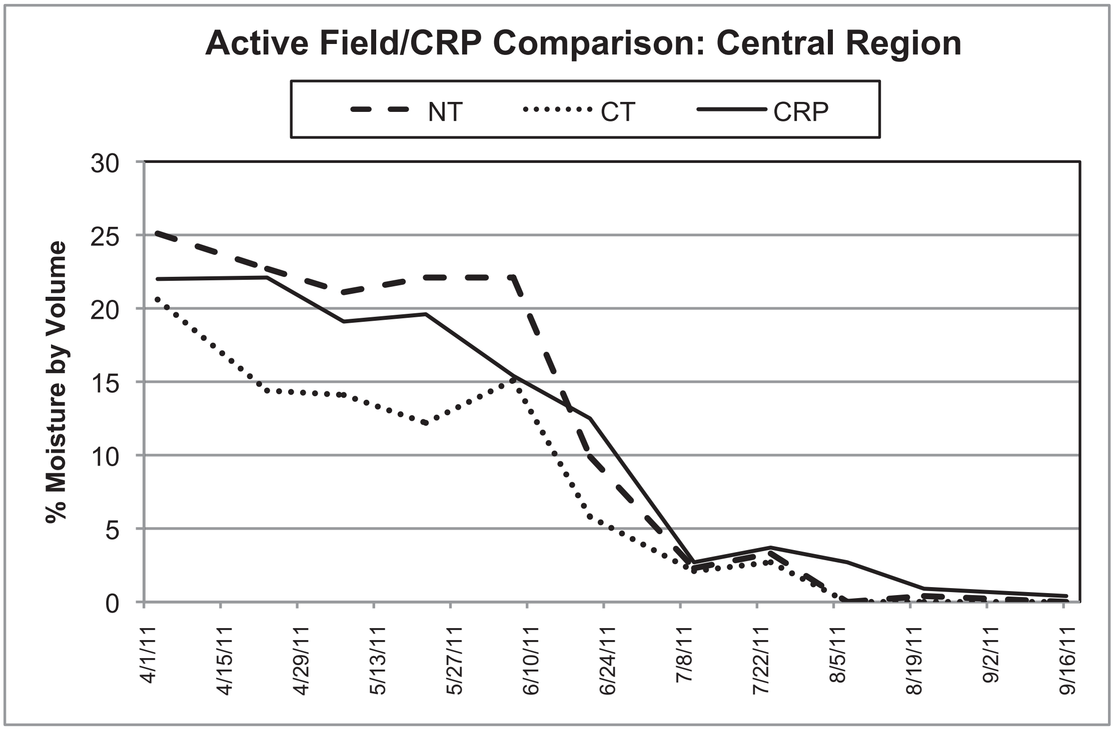

Figure 5.3. Active comparison: Central region

Southern Region

Like the Central region, NT soil moisture values in the Southern region (Figure 5.4) started out higher than CT values at the time of soil thaw. Soil moisture for the NT field began at 26%, while the CRP field started just above 20%, and the CT field started at 20% soil moisture by volume. Also like the Central region, NT held more moisture than CT longer into the summer, falling to similar levels in the end of June. While initially the CRP field had less moisture than the NT field, it held more moisture than both CT and NT after June 7, 2011. As was found with the other regions, the fields growing wheat depleted all available moisture from the soil, measuring at 0% moisture at the time of harvest. CRP fields, though variable in the amount of water at the end of the study, still contained 2% moisture in the soil to continue to sustain the native vegetative cover in the field.

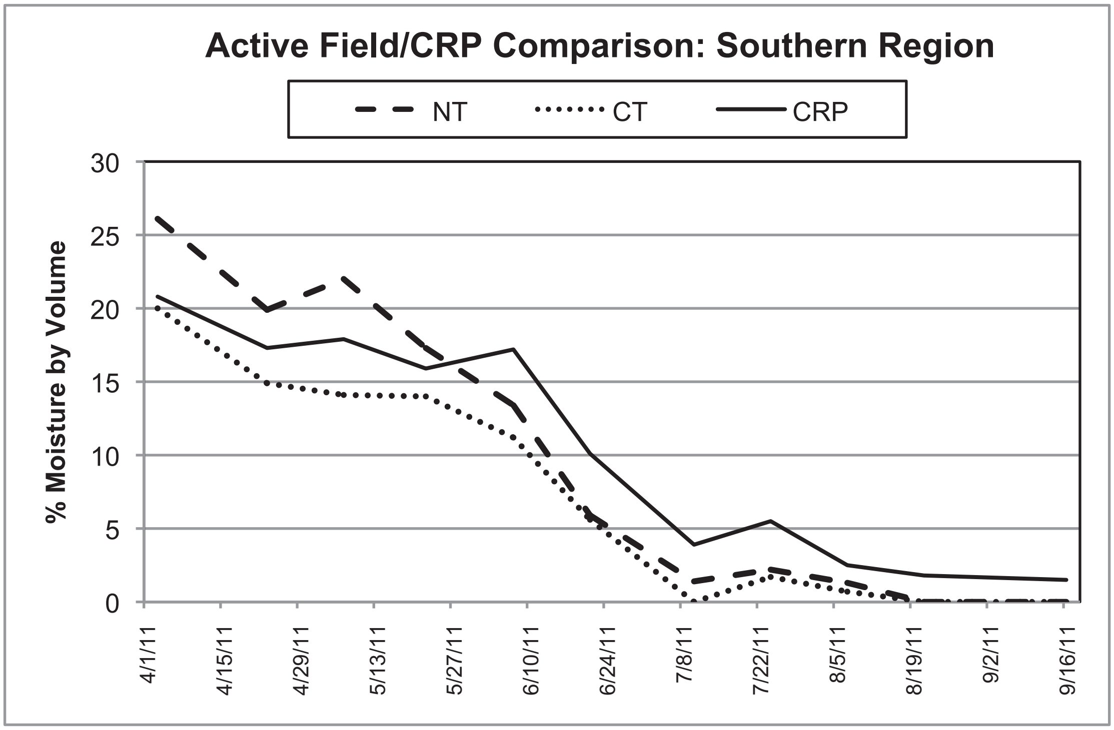

Figure 5.4. Active comparison: Southern region

Active Comparisons by Region

A comparison of CT soil moisture values by region (Figure 5.5) shows that the Northern region had markedly higher moisture values for the majority of the study, while the Central and Southern values were very similar. The Northern region initially started at 25% percent, while the Central and Southern regions started out at 20% after the soil thawed. Additionally, CT fields in the Northern region consistently held more soil moisture longer into the year, only dropping to the levels of the Central and Southern region at the beginning of August.

One explanation for the differences could be attributed to the difference in soil map unit between the Northern region (Siweeka) and the Central and Southern (Touhey). While the soils appeared similar enough to be compared in the study, they are sufficiently different to be classified as different map units. Minor variations between soil map units could account for the differences I found. Additionally, variations in regional precipitation and degree of stone coverage (see discussions below) could account for the differences found.

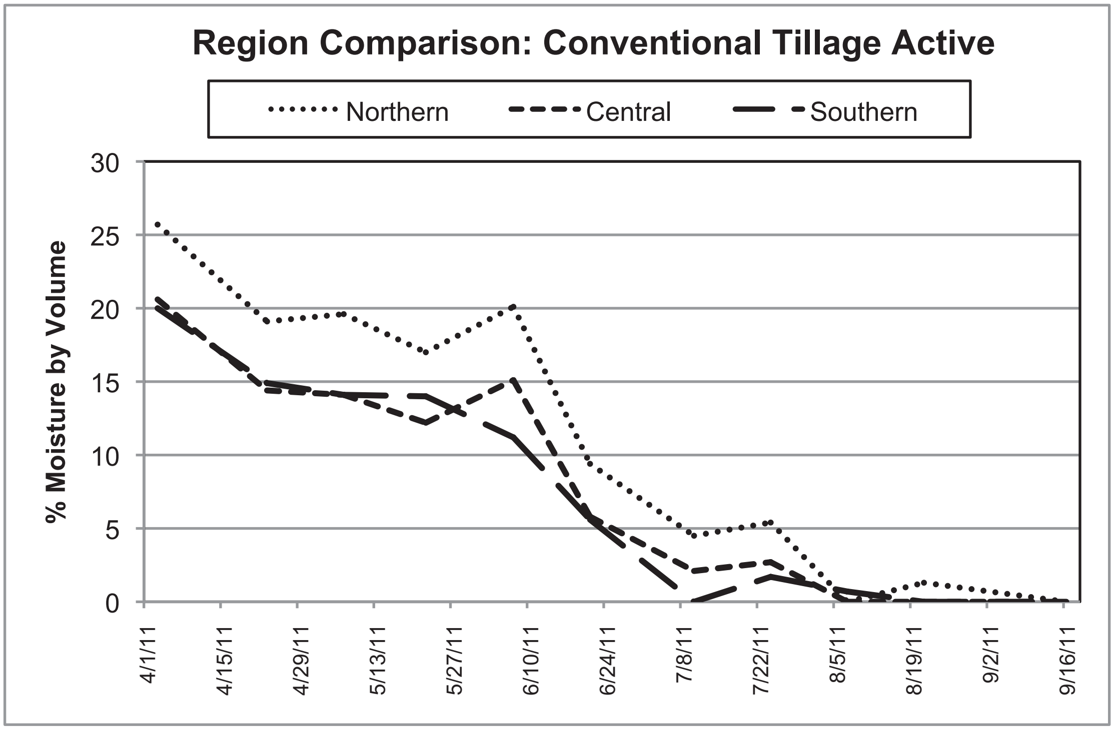

Figure 5.5. Regional comparison of CTA soil moisture values

A comparison of NTA soil moisture values by region (Figure 5.5) shows different results. The Northern region started out with the least amount of moisture, at 21% soil moisture by volume, compared to 26% moisture in the Southern region and 25% moisture in the Central region. With few exceptions, the NT field in the Central field held more moisture longer into the summer than the Northern or Southern regions. At the end of

June the Northern and Central regions had similar values, while the Southern region had several percentage points lower soil moisture by volume. By harvest time, all fields had similar soil moisture values, having exhausted all available soil moisture during wheat growth.

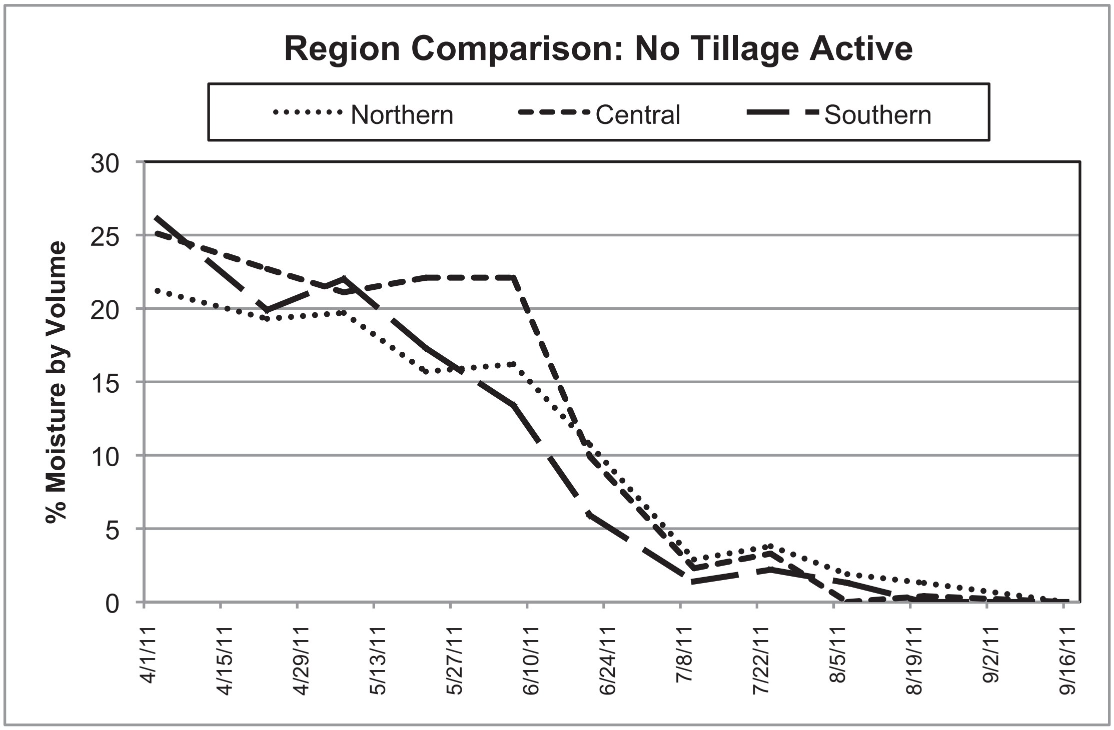

Figure 5.6. Regional comparison of NTA soil moisture values

A regional examination of the active field soil moisture values shows that in general, CT held more moisture in the Northern region than in the other regions. Conversely, NTA held more moisture in the Central region than the other regions. In both the Southern and Central regions, NTA held more moisture longer into the growing season than CTA. The opposite was true in the Northern region, where CTA held more moisture longer into the growing season. CRP held more moisture during the growing season than both CTA and NTA on active fields. This could be attributed to CRP being a functioning ecosystem with dryland-adapted plants. In this environment, growth only occurs when it can be sustained with available moisture. In both CTA and NTA, the water needs of the wheat plantings could exceed the available soil water, because it does not need to survive beyond harvest time.

Why would there be such stark differences in soil moisture by land use type between the regions? These differences could be attributed to differences in precipitation received in each region (see discussion below). It could also be due to the fact that the Northern region has a different soil type (Siweeka) than the Central and Southern regions (Touhey). While all CT and NT active fields held 0% moisture by harvest time, it does seem that any amount of soil moisture conservation during the hot, dry, growing season would be beneficial to the wheat crop. Schillinger, et al. (2008), Donahue, et al. (1983), and Shunqing, et al. (2003), all found an increase in yield with an increase in available moisture.

Fallow Field/CRP Comparisons

Fallow fields under Conventional Tillage (CTF) and No Tillage (NTF) were compared to fields enrolled in CRP. CRP fields were chosen as a control group approximating natural conditions and compared to the bare soil of CTF and the stubble cover of NTF. Soil moisture values were analyzed from April 3, 2011, when the soil had thawed to September 16, 2011, after time of seeding.

Northern Region

A comparison of soil moisture values in the Northern region (Figure 5.7) shows that after the thaw of the soil, NT initially started out with higher moisture values (27%) than CT (24%) and CRP (21%). Soil moisture values for each land use fluctuated throughout he spring until the beginning of June, when CT had significantly more soil moisture than NT and CRP. As the summer progressed, both NT and CRP moisture values dropped, while the drop in CT values was not as dramatic. For example, between June 21, 2011 and July 10, 2011, NT and CRP values dropped by roughly 9%, while during the same time period, CT values dropped by 3%.

The fallow CT field in the Northern region had more moisture than the NT fallow field at time of seeding, containing 15% soil moisture compared to 11% moisture respectively. This added moisture could make a large difference in the survival and viability of the subsequent wheat crop, as supported by Unger (2002), Schillinger and Young (2004), and Stewart (2011). CRP moisture values dropped throughout the study period, ending with a final soil moisture value of 4%.

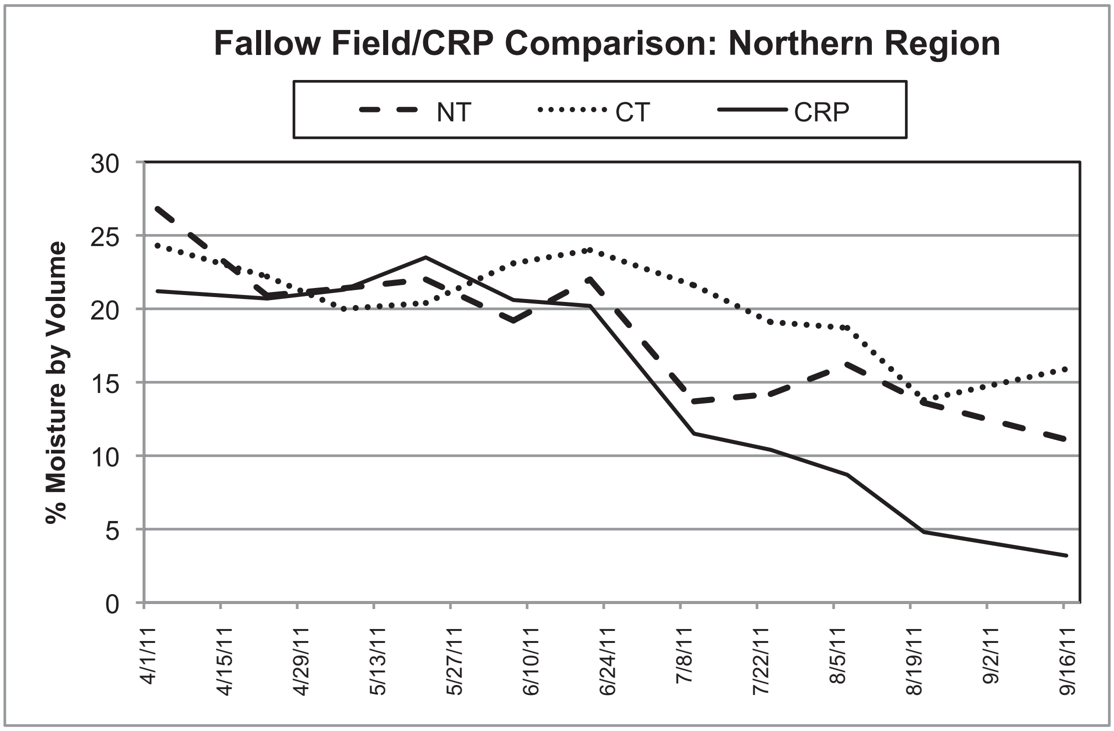

Figure 5.7. Fallow comparison: Northern region

Central Region

A comparison of soil moisture values in the Central region (Figure 5.8) shows that after the thaw of the soil, CT initially started out with higher moisture values (29%) than NT (25%) and CRP (22%). CT and NT soil moisture values were the same on the April 23, 2011 sample date. Following the April 23, 2011 sample, CT soil moisture values fell below NT soil moisture values and remained below NT until the end of the study. From April 23, 2011 until the beginning of September, the CT field contains roughly 5% less moisture than the NT field. At the time of seeding however, both CT and NT contained 15% moisture by volume in the soil. Following the April 23, 2011 sample date, CRP values continued to drop, ending the study at 1% moisture.

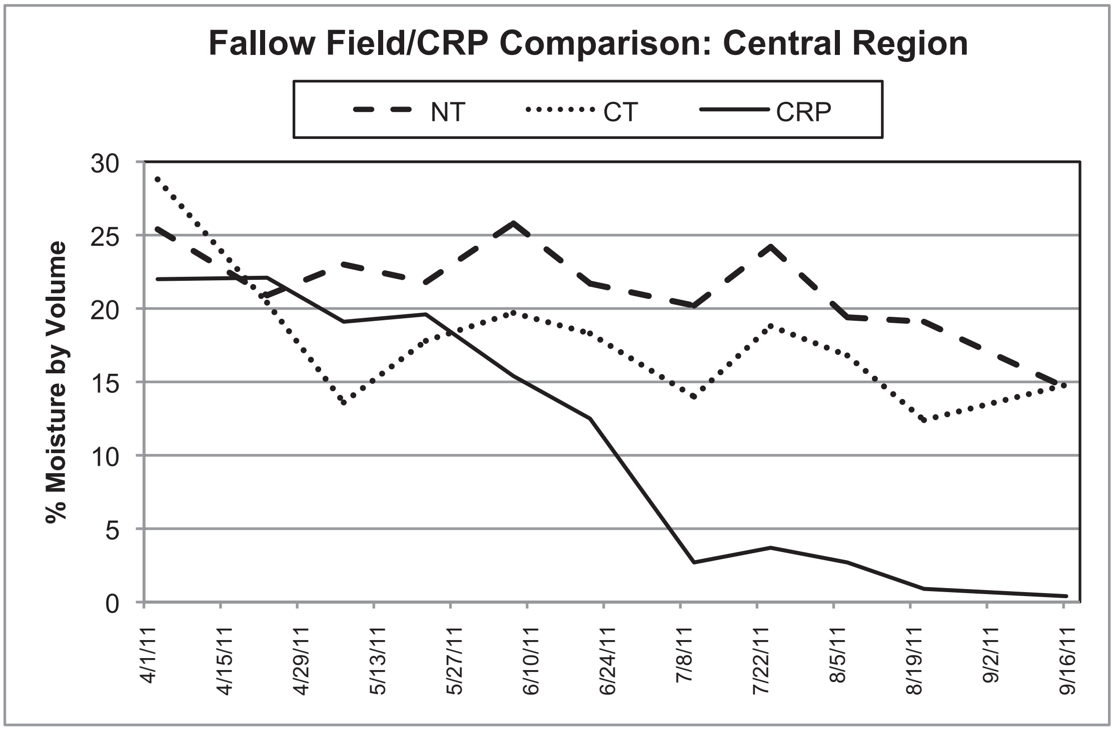

Figure 5.8. Fallow comparison: Central region

Southern Region

A comparison of soil moisture values in the Central region (Figure 5.9) shows that after the thaw of the soil, NT initially started out with higher moisture values (23%) than CT (20%) and CRP (20%). Soil moisture values for NT remain higher until the June 10, 2011 sample date when values became similar until after August 7, 2011 when CT held more moisture. The CT field continued to hold more moisture until time of seeding, when it contained approximately 5% more moisture than the NT field. Like the other regions, the CRP moisture values began to drop following the April 23, 2011 sample date. The Southern CRP field ended the study with 2% moisture in the soil.

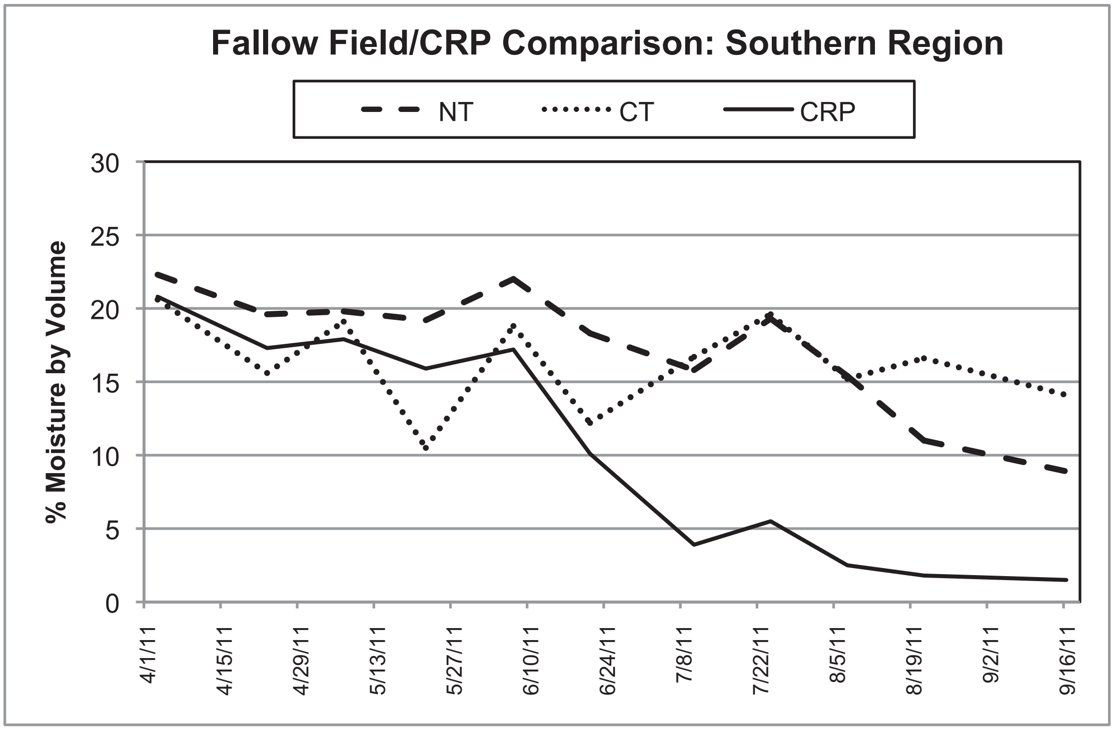

Figure 5.9. Fallow comparison: Southern region

Fallow Comparisons by Region

Soil moisture values for CT fallow (Figure 5.10) shows that the Central region had the highest initial soil moisture value after the soil thawed (28%), compared to the

Northern region at 25% and the Southern region at 21%. The Central region lost moisture dramatically during the month of April, while soil moisture loss in the Northern region was less pronounced. The Northern region held the most moisture through the spring until July 24, 2011, when moisture values were similar for all regions. Soil moisture values for all regions fluctuated slightly between July 24, 2011 and the time of seeding, when moisture values for all regions were approximately 15%.

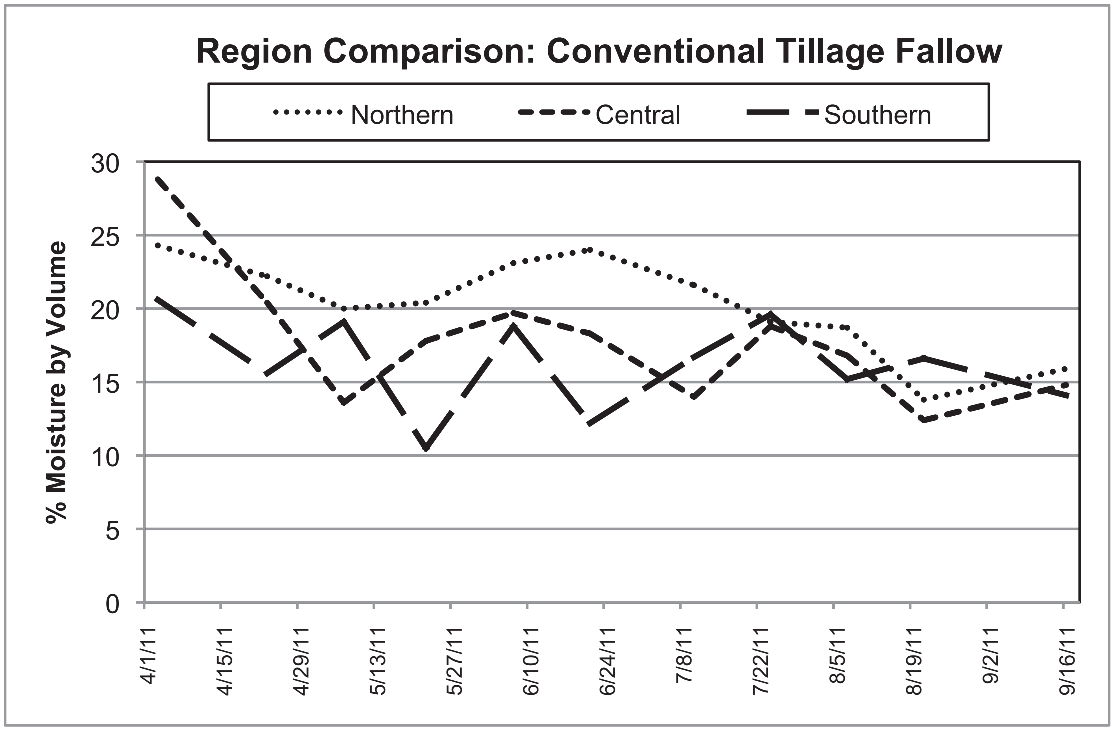

Figure 5.10. Regional comparison of CTF soil moisture values

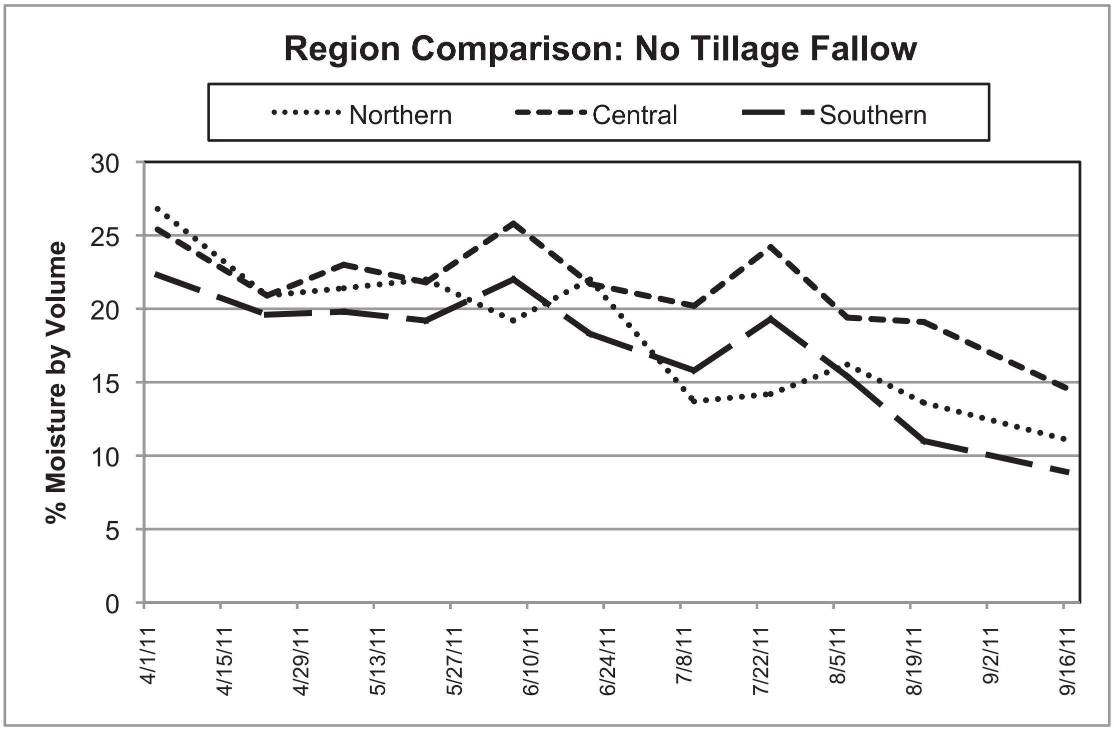

Figure 5.11. Regional comparison of NTF soil moisture values

Soil moisture values for NT (Figure 5.11) show the Northern region had the highest initial soil moisture (27%), while the Central region started with 25% and the Southern region started with 23% soil moisture after thaw. The Central region consistently had the highest soil moisture throughout the study. At the time of seeding the Central area had 15% soil moisture, compared to 11% in the Northern region and 9.5% in the Southern region.

The CT fallow fields in the Northern region had higher moisture values during the spring and summer than the NT fallow fields, while the NT fallow fields in the Central region had higher values than the CT fields for the majority of the study. In the Southern region, NT held more moisture initially, but CT fallow fields ended up with higher moisture values later into the year. In all cases, CRP had much lower moisture values than CTF and NTF throughout the year. This result would imply that both fallow methods are more effective than natural conditions at conserving soil moisture.

Possible reasons for why the results vary by region are similar to those stated earlier. It is possible that precipitation is different between regions, or that the differences in soil type have an effect on moisture storage by land use type. The stubble of NTF has been shown to trap more snow than the bare soil of CTF (Unger et al., 2006). Blowing snow is concentrated in areas where vegetation is present, leading to the increased potential for meltwater infiltration (Chung & England, 2006). The increased soil moisture from trapped snow could account for the higher initial soil moisture value in the Central and Southern NTF fields.

A possible reason for the differences and an explanation for why the NTF moisture values fell below CTF values in the Southern region could be the presence of weeds. CTF clears the land not only of stubble, but of weeds as well. NTF retains the stubble from the previous crop and while in fallow there are often weeds growing in these fields. Vegetation was growing on CRP throughout the study, while CTA and NTA were both growing wheat. The only field type without vegetative cover was CTF. Weeds reduce soil water during fallow and compete directly with crops for soil water, space, light and nutrients during the growing season (Unger et al., 2006). As temperatures increased from spring into summer, evapotranspiration rates of the growing weeds increased as well, which depleted soil water (Stewart, 2010). While it does not completely explain the differences, it might be a portion of the explanation of the findings.

Furthermore, it was hypothesized that since slope segments on the same soil map unit should have the same infiltration rate, and precipitation was low in the study area, moisture differences between the summit and toe slope positions should be minimal. A Wilcoxon rank sum test was completed and no significant difference was found between the moisture values of the summit and the toe slope positions ($p > 0.05$).

Soil Moisture and Land Use Statistical Analysis

Soil moisture data were statistically analyzed in relation to land use treatment using the Kruskal-Wallis test with a significance level of $p < 0.05$. This multiple comparison test was chosen to determine if differences existed between soil moisture and land use. Data were compared in a variety of ways. Data from all three regions were combined and analyzed. The data were examined by a common land use treatment (Northern CTA, Central CTA, and Southern CTA, for example) and by a common region (Northern CTA, NTA and CRP, for example). The CRP data was also examined separately. Analysis in all cases yielded non-significant results. The null hypothesis that samples have the same medians is not rejected. This can be interpreted to mean that all land use soil moisture comparisons gave similar results and that the groups were not significantly different from each other.

Soil moisture values were then compared by land use using the Wilcoxon rank sum test with a significance level of $p < 0.05$. This test examines a paired comparison of values to determine if a difference in soil moisture exists between treatments. Data were compared by common region (Northern CTF was compared to Northern NTF, for example). Additionally, data from all regions were combined and compared. No significant difference between treatments was found.

The fallow data was further divided into spring (April 3 to June 21, 2011) and summer (July 10 to September 16, 2011) and analyzed with a Wilcoxon rank sum test. No significant difference in soil moisture was found between fallow land uses when examined regionally or combined. Finally, CTF was compared to NTF from just prior to seeding (August 7 to September 16, 2011) and analyzed with the Wilcoxon rank sum test. Again, no significant difference in soil moisture was found between fallow land use treatments. Therefore, choice of tillage had no effect on soil moisture.

Soil moisture and land use data were then analyzed in regional pairs using the Wilcoxon matched pairs test. Data were divided based on common land use treatment and compared to other regions with the same treatment (NTF – Northern/Central, Central/Southern, Southern/Northern, for example) (Table 5.1). Significance level was set at $p < 0.05$.

Table 5.1.

Wilcoxon Matched Pairs Soil Moisture Land Use Comparison

Land Use	*p* value	Median	Inter-Quartile Range
NCTA/CCTA	0.045	10.2/7.6	14.3/17.6
SCTA/NCTA	0.003	11.9/10.2	20.3/14.3
NCTF/CCTF	0.019	19.6/15.4	8.8/5.9
SCTF/NCTF	0.038	15.8/19.6	7.2/8.8
NNTF/CNTF	0.014	15.2/17.1	9.9/8.9
CNTF/SNTF	0.001	17.1/20.6	8.9/8.9
NCRP/CCRP	0.012	11.9/8.5	13.1/14.2
SCRP/NCRP	0.001	11.9/12.6	13.1/16.5

A significant difference in soil moisture was found between CTA in the Northern region and both the Southern and Central regions. A comparison between NCTA and CCTA (p = .045, Median 10.2/7.6, Inter-quartile Range 14.3/17.6) shows that the median is significantly higher in the Northern site with a greater range of variability in the Central site. When SCTA is compared to NCTA (p = .003, Median 11.9/10.2, Inter-quartile Range 20.3/14.3), the median is significantly higher with a greater range of variability in the Southern site.

A significant difference in soil moisture was found between CTF in the Northern region and both the Southern and Central regions. A comparison between NCTF and CCTF (p = .019, Median 19.6/15.4, Inter-quartile Range 8.8/5.9) shows that the median is significantly higher with a greater range of variability in the Northern site. When SCTF is compared to NCTF (p = .038, Median 15.8/19.6, Inter-quartile Range 7.2/8.8), it also shows that the median is significantly higher with a greater range of variability in the Northern site.

A significant difference in soil moisture was found between NTF in the Northern and Central regions. A comparison between NNTF and CNTF (p = .014, Median 15.2/17.1, Inter-quartile Range 9.9/8.9) shows that the median is significantly higher in the Northern site with a greater range of variability in the Central site. A significant difference in soil moisture was also found between NTF in the Central and Southern regions. When CNTF is compared to SNTF (p = .001, Median 17.1/20.6, Inter-quartile Range 8.9/8.9), it also shows that the median is significantly higher in the Southern region and the range of variability is the same in both regions.

A significant difference in soil moisture was found between CRP in the Northern region and both the Central and Southern regions. A comparison between NCRP and CCRP ($p = .012$, Median 11.9/8.5, Inter-quartile Range 13.1/14.2) shows that the median is significantly higher in the Northern region with a greater range of variability in the Southern site. When SCRP is compared to NCRP ($p = .001$, Median 11.9/12.6, Inter-quartile Range 13.1/16.5), it also shows that the median is significantly higher with a greater range of variability in the Southern site.

In all regions, NTA fields gave non-significant results, which means that soil moisture values were not significantly different. With the exception of the NTF comparison, no significant difference in soil moisture was found between the Central and Southern region. Both of these regions share the same soil map unit (Touhey). Soil moisture values for the Northern region were significantly different than both the Central and Southern region in the CTA, CTF, and CRP comparisons. This could be attributed to differences in the soil map unit (Siweeka/Touhey). A Wilcoxon rank sum test was run and no significant difference was found between the moisture values of the Siweeka soil map unit and the Touhey soil map unit ($p > 0.05$). These soils are very similar, but they are mapped as different map units, meaning that differences exist.

While soil map units generally contain more than one soil series, and are usually named for the dominant soil series, soil complexes are named for soils that contain more than 15% dissimilar inclusions (Soil Survey Division Staff, 1993). This definition implies that differences exist not only between map units, but within map units. To further that point, Unger et al. (2006) found different degrees of aggregation and variations in macropore space within soils of the same texture. More study is needed to determine if the differences in soil map units explain why differences were found in the CT and CRP fields, but no significant differences were found in the NTA fields and between the NNTF and SNTF fields.

Another possible explanation for differences between the Northern region and the Central and Southern regions could be the presence of surface stones, and degree of stone coverage for each region. Wainwright, Mulligan, and Thornes (1999) found that stones at the surface had an impact on infiltration of precipitation. Stones resting on the surface allowed infiltration, while stones that were partially buried in the soil blocked infiltration. For example, in the CTF fields (Figures 5.12, 5.13 & 5.14) stones make up a large percentage of surface coverage in the Northern region while there were considerably fewer stones found at the surface in the Central and Southern regions. The differences in stone cover might account for the variations in soil moisture.

Figure 5.12. Surface rocks in Northern CTF. 6/7/11.

Figure 5.13. Surface rocks in Central CTF. 6/7/11.

Figure 5.14. Surface rocks in Southern CTF. 6/7/11.

Precipitation

Precipitation data were collected using the Watchdog® weather station from September 1, 2010 – September 16, 2011 (Table 5.1). These data show the highest precipitation totals occurred in May (78.23 mm), followed by March (61.98 mm). The Watchdog® recorded the precipitation from September 1, 2010 – September 1, 2011 as 327 mm.

Table 5.2

Watchdog® Precipitation Data,

September 1, 2010 to September 16, 2011

Month	Precipitation (mm)	Annual Precipitation (mm)
September	19.30	
October	29.72	
November	20.57	
December	43.69	
January	22.35	
February	11.18	
March	61.98	
April	6.10	
May	78.23	
June	25.40	
July	8.38	
August	0.00	327
September (1-16th)	0.00	327

Watchdog® precipitation values were compared to the rain gauge precipitation values from April 3, 2011 to September 16, 2011 (Table 5.3). Values were similar, indicating that the All Weather® rain gauges performed almost as well as the digital tipping bucket gauge. The Watchdog® recorded 137 mm of precipitation for the time period, while the Farmhouse gauge located next to it recorded 116.4 mm of precipitation. The Northern rain gauge recorded 97.0 mm, the Central rain gauge recorded 116.2 mm and the Southern rain gauge recorded 95.4 mm. Results would indicated that the Central area received the most precipitation, followed by the Northern region, then Southern region.

Table 5.3

Rain Gauge and Watchdog® Precipitation Values

Sample date	Northern	Central	Southern	Farmhouse	Watchdog®
4/3/11	14.2	18.1	21.1	13.8	21.9
4/23/11	3.7	3.8	3.8	4.0	4.3
5/7/11	9.4	10.0	9.0	8.1	9.9
5/22/11	24.2	33.6	23.4	28.0	32.0
6/7/11	39.5	44.8	34.2	43.0	47.2
6/21/11	3.8	3.1	2.8	14.2	16.3
7/10/11	0.0	0.0	0.0	0.0	0.3
7/24/11	2.2	2.8	1.1	3.3	2.3
8/7/11	0.0	0.0	0.0	2.0	2.8
8/21/11	0.0	0.0	0.0	0.0	0.0
9/16/11	0.0	0.0	0.0	0.0	0.0
Total (mm)	97.0	116.2	95.4	116.4	137.0

Rain gauge values for all rain gauges from April 3, 2011 – September 16, 2011 were statistically analyzed using a Kruskal-Wallis test with a significance level of $p < 0.05$. This test was chosen to determine if differences exist between rain gauge values. The test yielded a p value of 0.94, showing that the precipitation values were significantly different from each other. This can be interpreted to mean that there were differences in precipitation across the study area.

Precipitation data from the Watchdog® tipping bucket gauge and the All Weather® Farmhouse gauge were statistically analyzed using the Spearman rank correlation test with a significance level of $p < 0.05$. This test was chosen to determine the strength of the link between the two sets of data. Results showed that the Watchdog® was positively correlated to the Farmhouse rain gauge located beside it with a Spearman's rho of 0.98 with a significance level of $p < 0.001$. This result indicates that the gauges collected similar precipitation amounts, and suggests the validity of the results of the other rain gauges in the study.

A Wilcoxon signed rank test was performed to determine if the medians of the rain gauge values were different. The Watchdog® tipping bucket gauge was compared to each regional All Weather® gauge. A significant difference was found between the Watchdog® tipping bucket gauge and the Northern and Southern All Weather® gauges ($p < 0.001$). No significant difference was found between the Watchdog® tipping bucket gauge and the Central, and Farmhouse All Weather® gauges ($p > 0.05$). This indicates that the Northern and Southern regions received different precipitation than the Central region, where the Watchdog®, Central, and Farmhouse gauges were located.

Soil Moisture and Precipitation Statistical Analysis

While precipitation data were collected throughout the year, only data collected from April 3, 2011 to September 16, 2011 were used for analysis. Precipitation and soil moisture data were statistically analyzed using the Spearman rank correlation test with a significance level of $p < 0.05$ (Table 5.4). Soil moisture values within each region (Northern, Southern, and Central) were compared to the precipitation gauge values in that region for each sample date to determine if a relationship existed between precipitation and the soil moisture of each field.

Spearman rank correlation showed a significant relationship between local precipitation and soil moisture in all CTA, NTA and CRP fields (r_s ranging from 0.79 to 0.88). Precipitation was strongly, positively correlated to soil moisture with a significance level of p <.001 to CTA (r_s = 0.87, 0.88, and 0.83) and NTA (r_s = 0.86, 0.85, and 0.87) in all regions and the CRP of the Central (r_s = 0.79) and Southern (r_s = 0.81) regions. Precipitation was somewhat strongly correlated to soil moisture of the Northern CRP field (r_s = 0.68). A positive correlation between NTA, CTA and CRP in all regions indicates that when precipitation values increase, soil moisture also increases.

Table 5.4

Spearman Rank Rain Gauge/Soil Moisture Correlation

Land use	r_s	p value
NORTHERN RAIN GAUGE/ SOIL MOISTURE		
NTA	0.86	<.001
CTA	0.87	<.001
CRP	0.68	<.001
CENTRAL RAIN GAUGE/ SOIL MOISTURE		
NTA	0.85	<.001
CTA	0.88	<.001
CRP	0.79	<.001
SOUTHERN RAIN GAUGE/ SOIL MOISTURE		
NTA	0.87	<.001
CTA	0.83	<.001
CRP	0.81	<.001

A possible explanation for the strong correlation could be vegetative cover, since all three land uses were actively growing vegetation. Plants intercept precipitation as it falls and aid in its infiltration into the soil (Shunqing et al., 2003). Additionally, the shading of the soil surface, provided by vegetation, slows evaporation of precipitation, allowing for additional opportunities for infiltration (FAO, 2011; Wainwright et al., 1999).

Precipitation was not significantly correlated to soil moisture in CTF and NTF fields ($p > 0.05$), which are designed to capture and retain moisture. One reason that a correlation was not found could be the presence of stored soil moisture from the previous year. Another possible explanation for the lack of a correlation is the presence of a surface mulch in both CTF and NTF. In a study in the drylands of Eastern Washington, McCall (1925) found that a dust mulch, as found in CTF, can prevent infiltration of precipitation if it has a surface crust. After a precipitation event the surface of the dust mulch can harden and cause precipitation to run off, rather than infiltrate. A stubble mulch, as is found with NTF, may also have a surface soil crust due to lack of tillage operations in the field which prevents infiltration of precipitation (Lindstrom et al., 1974).

Infiltration at the time of a precipitation event depends on the ability of the soil to receive moisture (Rodriguez-Iturbe & Porporato, 2004; Wild, 1993). Duration and intensity of precipitation events, as well as the spatial variability of precipitation in the study area can impact infiltration into fallow fields. Low intensity, scanty precipitation might not infiltrate through the surface mulch or may be evaporated before infiltrating into the soil (Horton et al., 1996). Additionally, high intensity, high volume precipitation might run off of the fallow surface, rather than infiltrate, whereas the vegetated surfaces, such as those found in CTA, NTA and CRP will slow runoff and increase infiltration of precipitation.

Temperature

The temperature data collected with the Watchdog® weather station shows that mean monthly temperatures were lowest in February (-8.6 °C) and highest in August (20.3 °C) (Table 5.5).

Table 5.5

Watchdog® Temperature Data, September 1, 2010 to September 16, 2011

Month	High Temp. (°C)	Low Temp. (°C)	Mean Monthly (°C)	Mean Annual (°C)
September	28.3	-0.6	13.9	
October	27.8	-4.4	11.7	
November	16.1	-25.0	-4.5	
December	5.0	-21.6	-8.3	
January	9.4	-21.6	-6.1	
February	7.8	-25.0	-8.6	
March	18.3	-6.7	5.8	
April	18.3	-7.8	5.3	
May	23.9	-3.9	10.0	
June	29.4	1.1	15.3	
July	32.8	1.7	17.3	
August	35.0	5.6	20.3	6
September (1-16th)	35.5	2.2	18.9	7.3

Soil Moisture and Temperature Statistical Analysis

Temperature and soil moisture data were statistically analyzed using the Spearman rank correlation test with a significance level of $p < 0.05$ (Table 5.6). Temperature data from each of the 14 days preceding the sample date were averaged and compared to soil moisture values within each area (Northern, Southern, and Central) to determine if a relationship existed between temperature and the soil moisture of each field.

Spearman rank correlation showed a strong, negative relationship between air temperature and soil moisture in all NTF, NTA, CTA, and CRP fields in all regions with r_s values ranging from -0.68 to -0.97. Air temperature was also strongly inversely correlated to soil moisture in the Northern CTF field (r_s = 0.71). A negative correlation indicates that when air temperature increases, soil moisture decreases.

Table 5.6.

Spearman Rank Air Temperature/Soil Moisture Correlation

Land use	r_s	*p* value
NORTHERN TEMPERATURE/ SOIL MOISTURE		
NTF	-0.81	0.002
NTA	-0.96	<.001
CTF	-0.71	0.014
CTA	-0.9	<.001
CRP	-0.87	<.001
CENTRAL TEMPERATURE/ SOIL MOISTURE		
NTF	-0.68	0.02
NTA	-0.95	<.001
CTA	-0.92	<.001
CRP	-0.97	<.001
SOUTHERN TEMPERATURE/ SOIL MOISTURE		
NTF	-0.87	<.001
NTA	-0.97	<.001
CTA	-0.96	<.001
CRP	-0.95	<.001

A correlation between increasing air temperature and decreasing soil moisture in NTF, NTA, CTA, and CRP fields could be explained by the presence of transpiring vegetation. NTA, CTA and CRP are all actively growing vegetation. The presence of weeds was noted in all NTF fields in all regions. As temperatures increase, vegetation removes moisture from the soil to replenish moisture loss through evapotranspiration (Horton, Bristow, Kluitenberg, & Sauer, 1996; Wild, 1993).

No correlation was found between air temperature and the Southern and Central CTF fields ($p > 0.05$). As found with precipitation, this could be due to the presence of a surface dust mulch (Phillips & Phillips; 1984; Schillinger, 2001; Schillinger et al., 2006). The dust mulch has an insulating effect forming a barrier between the atmosphere and the stored soil moisture below (Lindstrom et al., 1974). The dust mulch would also reduce evaporation and conserve moisture in the seed zone as temperatures rose (Bewick et al., 2007; Riar et al., 2010). Unlike the Southern and Central regions, the CTF field in the Northern region showed a strong negative correlation between air temperature and soil moisture. This could be attributed to the difference in soil map unit as discussed previously, as the Northern region had Siweeka soil, and the Southern and Central region contained Touhey. Additionally, the presence of surface stones (see previous discussion) could explain the regional differences in CTF moisture. More study is needed to determine why differences exist between CTF and all other treatments and why the NCTF field showed a correlation, when the SCTF and CCTF did not.

Evapotranspiration Statistical Analysis

The lack of usable study area evaporation data necessitated the use of supplemental grass evapotranspiration data from the St. Andrews weather station (7.9 km from the study area) operated by WSU for analysis. Low winter evaporation rates dictated that analysis was performed with samples between April 1, 2011 and September

16, 2011. Prior to utilizing St. Andrews evapotranspiration data for analysis, a Spearman rank correlation between the Watchdog® weather station temperature data, and the St. Andrews site temperature data for April 1, 2011 to April 16, 2011 was performed (Figure 5.15). The Spearman Rank test showed the two to be strongly positively correlated (r_s =.97, p = <.001).

A Wilcoxon signed rank test was then run on the same temperature data to determine if there were differences between the two data sets. The analysis confirmed that the data were not significantly different from each other ($p > 0.05$).

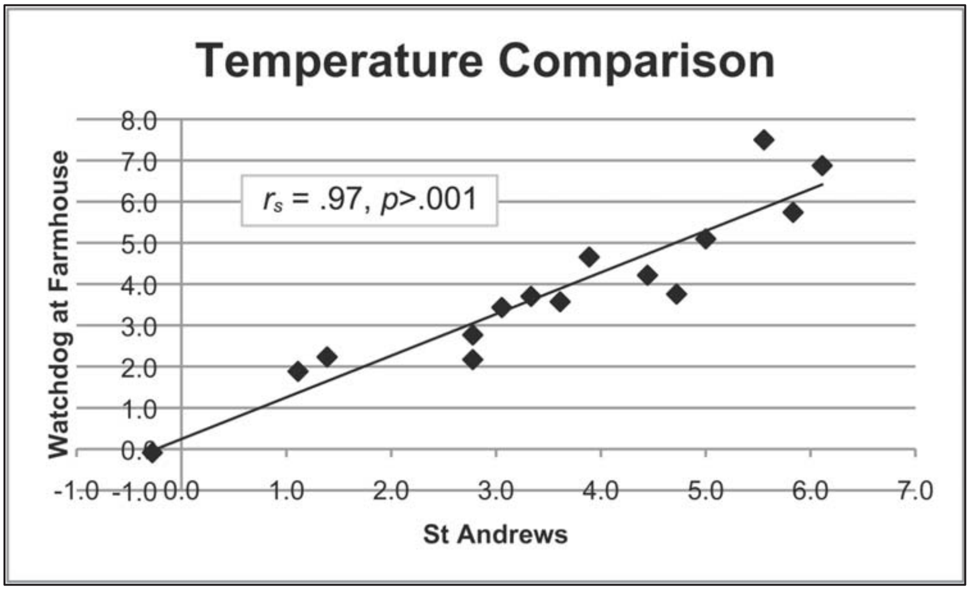

Figure 5.15. Comparison of weather station temperature data April 1, 2011 through April 16, 2011.

Soil Moisture and Evapotranspiration Statistical Analysis

Evapotranspiration and soil moisture data from the St. Andrews weather station site were statistically analyzed using the Spearman rank correlation test with a significance level of $p < 0.05$ (Table 5.7). Evapotranspiration data from each of the 14 days preceding the sample date were averaged and compared to soil moisture values within each area (Northern, Southern, and Central) to determine if a relationship existed between grass evapotranspiration and the soil moisture of each field.

Spearman rank correlation showed no significant relationship between evapotranspiration and CTF fields in all regions ($p > 0.05$). However, strongly significant negative relationships were found between evapotranspiration and soil moisture in all CTA, NTA, and CRP fields (r_s values ranging from -0.82 to -0.91), and the Northern ($r_s =$ -0.67) and Southern ($r_s =$ -0.72) NTF fields ($p < 0.05$).

Table 5.7

Spearman Rank Evapotranspiration/Soil Moisture Correlation

Land use	r_s	p value
NORTHERN EVAPOTRANSPIRATION/ SOIL MOISTURE		
NTF	-0.67	0.033
NTA	-0.84	<.001
CTA	-0.82	<.001
CRP	-0.78	<.001
CENTRAL EVAPOTRANSPIRATION/ SOIL MOISTURE		
NTA	-0.87	<.001
CTA	-0.84	<.001
CRP	-0.86	<.001
SOUTHERN EVAPOTRANSPIRATION/ SOIL MOISTURE		
NTF	-0.72	0.019
NTA	-0.87	<.001
CTA	-0.91	<.001
CRP	-0.84	<.001

No significant correlation was found between evapotranspiration and soil moisture in all CTF fields and the Central NTF ($p > 0.05$). This could be attributed to the mulch associated with fallow tillage methods (Unger et al., 2006). A powdery dust mulch, as is found in CTF, is effective at reducing evaporation of stored soil moisture by breaking the capillary movement of soil water to the surface (Papendick, et al., 1973; Bewick, et al., 2007; Schillinger et al., 2006). A standing stubble mulch, as is found with NTF, shades the soil surface which reduces evaporation, and has been found to be an effective method of conserving water in the seed zone area (Lindstrom et al., 1974). Additionally, NTF stubble mulches have a high albedo, which reflect solar radiation and reduce evaporation by a reduction in soil surface temperature (Horton, Bristow, Kluitenberg, & Sauer, 1996).

The CTA, NTA, and CRP fields have vegetative cover, which interacts with the environment differently than a bare-soil dust mulch, or a stubble mulch. In all CTA, NTA and CRP fields plants are actively transpiring, which would result in a strong negative correlation between soil moisture and evapotranspiration. Additionally, weeds were actively growing on the NTF fields in the study area. Weeds have been shown to reduce soil moisture in dryland environments (Riar et al., 2010). The degree of weed coverage and length of time that weeds were present in NTF fields was not quantified during the study. Differences in weed coverage could account for differences in the correlations between soil moisture and evapotranspiration within the NTF data set.

An additional factor to consider when examining statistical results is the influence of wind. Wind has been shown to increase evaporation of soil moisture (Brouwer et al., 1985; FAO, 2011; Wild, 2003). Due to the prohibitive cost of the equipment and the travel distance to the study site, wind was not a variable that was included in the study design. While exclusive wind data was not used, the evapotranspiration data from St. Andrews weather station that was utilized in this study includes the factor of wind. Study results therefore, included wind effects in the evaporation analysis. Wind likely has an influence on the evaporation rates in the study area, where it is very windy (Cornelius, 2006; Nicholson, 2011). Vegetative cover type and field orientation in relation to wind direction could also have an effect on evaporative rates (Nicholson, 2011; Unger, 2006).

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

The overall purpose of the study was to examine soil moisture in relation to land use in the dryland winter wheat agricultural fields in eastern Douglas County, near Mold, Washington. Specifically, I measured and analyzed the seasonal variation of soil moisture in conventional tillage and no tillage fields, both fallow and active, as well as CRP lands, while considering the factors of precipitation, air temperature, and evaporation, with constant topography and soil texture.

Soil Moisture and Land Use

No difference in soil moisture was found between tillage practices; therefore, choice of tillage has no significant effect on soil moisture. This finding has significant implications for management decisions on farms in the study area and beyond. Given the similarity of soil moisture between CT and NT, it is my recommendation that farmers in the study area and adjacent drylands adopt lower cost NT farming methods.

Study results indicate that NT could increase dryland farming efficiency and profitability (Blevins et al., 1984; Gillespie, 2008, Heer & Krenzer, 1989; Lueschen et al., 1991; NRCS, 2011; Rair et al., 2010). Studies in Eastern Washington have shown both NT and CT to be economically comparable when considering returns and production costs (Juergens et al., 2004; Janosky et al., 2002). NT has been shown to have lower on-the-farm costs and require less labor for farm operations, as compared to CT. There appears to be little economic risk in switching from CT to NT (Janosky et al., 2002; Schillinger, 2001). Additionally, cost share incentives exist through the Natural Resources Conservation Service (NRCS) to aid farmers in their transition from CT to NT.

Farmers who switch from CT to NT will decrease erosion, reduce surface runoff, and improve the health of their soil (Griffith et al., 1986; Kok et al., 2009; Martin et al., 1991). The reduction of soil erosion with NT will extend the productivity of the land by retaining organics and nutrients, allowing a farmer to sustainably produce crops (Griffith et al., 1986). Due to the nature of the NT method, the more crops a farmer produces, the more nutrients are added to the system (Cresswell & Martin, 1993). Additionally, macropores in the soil increase with time, allowing for additional infiltration of precipitation.

However, disadvantages of the switch could include the cost of new equipment, a drop in initial crop yields, weeds, additional monetary and environmental costs of more herbicides, as well as learning and applying new seeding techniques (Juergens et al., 2004; Kok et al., 2009; Schillinger et al., 2006; Schillinger, Papendick, Guy, Rassmussen, & Van Kessel, 2006). Other limiting factors in switching from CT to NT include: leasing land rather than owning it, variability of what crops are grown, the size of the farm, and what equipment is already owned (Kok et al., 2009).

The soils in all fields, in all three regions, gained moisture throughout the fall and winter, and reached their maximum moisture over the winter. Moisture values fluctuated throughout the spring and into summer. Overall, soil moisture in all fields steadily declined from the beginning of June until the end of the study. This finding coincided with a decrease of overall precipitation.

A difference in soil moisture values was found between regions. In both the active and fallow comparisons, the CT fields held more moisture longer into the year in the Northern region than in the Central or Southern regions. Conversely, NT held more moisture in the Central region than the other regions, and held it longer into the growing season than CT. It is suspected that the difference in soil map units might explain the results. Sample sites in the Northern region shared the Siweeka soil map unit, while the sample sites in the Central and Southern regions shared the Touhey soil map unit.

While CRP fields held more moisture during the growing season than both CT and NT active fields, they had much lower moisture than CT and NT fallow fields throughout the study period. This result would imply that CRP fields transpired more moisture than the CTA and NTA fields, and that both fallow methods effectively conserved soil moisture compared to natural conditions. Leaving fields fallow for a year does improve soil moisture storage in the study area.

Soil Moisture and Precipitation

The study found that precipitation is strongly correlated to soil moisture in all CTA, NTA, and CRP sites across all regions. The presence of actively growing vegetation on the CTA, NTA and CRP fields is a likely explanation for the correlation. Plants intercept precipitation as it falls and provide openings and channels along root systems for water to infiltrate into the soil. Additionally, vegetation shades the soil surface, slowing evaporative losses and allowing more time for infiltration. Precipitation was not significantly correlated to soil moisture in CTF and NTF fields.

The presence of a surface mulch, and soil moisture carried over from the previous year could account for the lack of a correlation between precipitation and CTF and NTF. It is possible that fallow fields are less responsive to individual precipitation events, due to the presence of stored moisture in the profile. Other potential factors include the duration and intensity of precipitation events as well as the spatial variability of precipitation in the study area.

Soil Moisture and Temperature

The study found a negative correlation between air temperature and soil moisture in NTF, NTA, CTA, and CRP fields. Possible causes are solar radiation, evapotranspiration and vegetation. As temperature increases, vegetation removes moisture from the soil to replenish moisture loss through evapotranspiration. NTA and CTA fields were growing wheat, while CRP fields continued growing native shrubs and grasses, and NTF fields were rife with weeds.

The CTF fields, the only ones not actively growing vegetation during the study, showed no significant correlation between air temperature and soil moisture in the Southern and Central regions. This could be due to the insulating effect of a dust mulch. The CTF field in the Northern region also had a dust mulch, but showed a strong negative correlation between air temperature and soil moisture. This finding could be attributed to the difference in soil map unit, or the greater amount of stones in the Northern region's soil. The stones, which were plentiful at the soil surface, could have decreased infiltration and increased evaporation by raising soil temperatures.

Soil Moisture and Evaporation

A significant negative relationship was found between evapotranspiration and soil moisture in all CTA, NTA, and CRP fields, and the Southern and Northern NTF fields. Results could be attributed to vegetation as discussed previously. All CTA, NTA and CRP fields are actively growing vegetation, and NTF fields had weeds.

No relationship was found between evapotranspiration and soil moisture in CTF fields across all regions. The dust mulch of CTF is effective at reducing evaporation of stored soil moisture by breaking the capillary movement of soil water to the surface. Further, no relationship was found between evapotranspiration and soil moisture in the Central NTF field. The NTF stubble mulch had a high albedo and shaded the soil surface, which reduced evaporation.

Future Research

Other research to enhance the findings of this study includes: examining long term weather data in relation to soil moisture, taking deeper soil samples, looking at the relationship between soil moisture and soil organics (stubble, roots, manure, etc.), examining the effects of wind on soil moisture, looking at the effects of soil temperature under different land uses, determining the effects of stones on infiltration of precipitation, and investigating the role of weeds in evapotranspiration and infiltration.

The current study examines a six month time period. Yearly weather is highly variable. The study period was a colder and wetter year than normal. The thirty year average annual temperature was 8.4 C° compared to the September 2010 to September 2011 average temperature of 6 C°. The thirty-year average annual precipitation for the study area was 293 mm, compared to the September 2010 to September 2011 average of 327 mm. Several years of temperature and precipitation data would provide a better representation of soil moisture in the study area as it relates to the variability of long-term climate data. Extended weather data collection in the same sites would further inform long-range land-use practices by shedding light on soil moisture changes over specific time periods.

The majority of precipitation in the study area falls as snow. While the rain gauges collected similar precipitation data to the Watchdog® weather station, neither gauge type was specifically equipped to gather snow data. Snowfall depths for each field could explain how snow infiltration impacts soil moisture. Furthermore, analysis of snow capture by vegetation could identify differences in available melt water between land uses.

Deeper soil moisture sample depths are recommended to get a more comprehensive picture of soil moisture in the study area. Wheat roots often reach beyond 1.2 m in depth. Therefore, a study that sampled to that depth would provide valuable information about soil moisture availability to wheat crops throughout the year.

An assessment of the type and percentage of organics in the soil of each field could further specify similarities and differences between land uses and/or regions. The soil structure associated with increased organics results in lower bulk density, which increases the water holding capacity of the soil. Multi-year data collection could also explain the impact of organics on soil structure over time.

While my study design included wind data in the evapotranspiration analysis, additional research regarding the relationship between wind and soil moisture is suggested. The study area is a very windy place. It is well known that winds decrease soil moisture by increasing evaporation at the soil surface. Data regarding wind direction and wind speed could aid in data analysis and further explain results.

A more directed study should be undertaken to determine the impacts of soil temperature on soil moisture. This could also include an examination of the effects of solar radiation and transpiration in relation to soil temperature. Future studies could take continuous readings with soil temperature probes to determine whether daily fluctuations in soil temperature impact soil moisture retention. This information could aid farmers in determining planting and harvesting times.

Degree of stoniness in each sampled field was not quantified during this study. It is recommended that future studies take stoniness into account to minimize variability between sample areas. Quantified data on the presence of stones in the fields could help to explain soil moisture differences between land uses and/or regions. Stones resting on the surface appear to increase infiltration, while partially buried stones block infiltration. Specific information on degree of coverage and type, size, and number of stones around the sample sites would help clarify the effects of stones on soil moisture.

Specific knowledge of the type and number of weeds at each sample site could be useful. This study did not quantify the species present nor the degree of weed coverage in sampled fields. Future studies should select fields with similar species composition and presence. Additionally, weed eradication methods also need to be studied. The increased need for herbicides under NT could have detrimental effects to soil organisms, resulting in fewer macropores and less water infiltration. Therefore, herbicides that do not disrupt the lifecycle of soil organisms should be identified.

The Global Picture

While local producers can benefit from switching to no tillage, this study has global relevance as well. The world’s supply of fresh water for irrigation is limited and strained by the pressures of increasing populations. As more people settle in dryland agricultural environments, due to decreasing land availability, it is imperative that precipitation be used as efficiently as possible for food production. This requires an understanding of how precipitation, evapotranspiration, wind, and crop management affects soil moisture. Diesel will likely get more expensive and less readily available as time goes on. The decreased fuel consumption of no tillage will allow farming in areas where the prohibitive costs of conventional tillage would not. As farming expands into more rain-fed areas, no tillage could become integral in efforts to maintain global food security in the future.

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APPENDIXES

APPENDIX A

SIWEEKA SOIL MAP UNIT DESCRIPTION (327)

SIWEEKA SERIES

The Siweeka series consists of moderately deep to duripan, well drained soils formed in loess and volcanic ash over glacial till over basalt bedrock on till plains on glaciated plateaus. Slopes are 0 to 65 percent. Average annual precipitation is about 14 inches and average annual air temperature is about 48 degrees F.

TAXONOMIC CLASS: Ashy over loamy, glassy over mixed, superactive, mesic Vitrandic Durixerolls

TYPICAL PEDON: Siweeka ashy fine sandy loam cropland, on a 6 percent north facing slope at 2,400 feet elevation. (Colors are for dry soil unless otherwise stated. All textures are apparent field textures)

Ap--0 to 9 inches; dark grayish brown (10YR 4/2) ashy fine sandy loam, very dark grayish brown (10YR 3/2) moist; weak fine granular structure; soft, very friable, nonsticky and nonplastic; many very fine, fine and common medium roots; few very fine irregular pores; 5 percent gravel and 10 percent sand-size pumice, 0.5 to 2.0 mm. in diameter; neutral (pH 7.1); clear wavy boundary. (6 to 10 inches thick)

A--9 to 16 inches; grayish brown (10YR 5/2) ashy fine sandy loam, very dark grayish brown (10YR 3/2) moist; weak fine subangular blocky structure; soft, very friable, nonsticky and nonplastic; common very fine tubular pores; 5 percent gravel and 15 percent sand-size pumice, 0.5 to 2.0 mm. in diameter; neutral (pH 7.1); clear wavy boundary. (0 to 8 inches thick)

AB--16 to 27 inches; grayish brown (10YR 5/2) gravelly ashy fine sandy loam, dark brown (10YR 3/3) moist; weak medium subangular blocky structure; soft, very friable, nonsticky and nonplastic; common very fine and few fine roots; common very fine tubular and few fine interstitial pores; 15 percent gravel, 5 percent cobbles and 15 percent sand-size ash, 0.5 to 2.0 mm. in diameter; neutral (pH 7.1); abrupt wavy boundary. (4 to 12 inches thick)

2Bk--27 to 36 inches; gray (10YR 5/1) gravelly fine sandy loam, dark grayish brown (2.5Y 4/2) moist; weak fine subangular blocky structure; slightly hard, very friable, nonsticky and slightly plastic; common very fine tubular pores; 15 percent gravel, 5 percent cobbles; common distinct discontinuous coatings of secondary carbonates on rock fragments; violently effervescent; moderately alkaline (pH 8.2); abrupt smooth boundary. (0 to 10 inches thick)

2Bkqm--36 to 42 inches; gray (5Y 5/1) weakly cemented duripan that crushes to very cobbly sandy loam, dark olive gray (5Y 3/2) moist with light brown (7.5YR 6/4) and very pale brown (10YR 8/2) moist, laminar caps; massive; very hard, extremely firm, nonsticky and nonplastic; few very fine interstitial pores; 25 percent gravel and 15 percent cobbles; many distinct continuous coatings of secondary carbonates and silica on surface and fractures of the duripan; violently effervescent; strongly alkaline (pH 8.6); clear wavy boundary. (4 to 10 inches thick)

2Cdk--42 to 60 inches; dark gray (5Y 4/1) very cobbly sandy loam, dark olive gray (5Y 3/2) moist; massive; hard, extremely firm; nonsticky and nonplastic; 30 percent gravel and 30 percent cobbles; few fine filaments of secondary carbonates in fractures and seams; violently effervescent; moderately alkaline (pH 8.1).

TYPE LOCATION: Douglas County, Washington. Approximately 3 miles southwest of Sims Corner; about 200 feet north and 200 feet east of southwest corner section 4, T.26N., R.28E. (Latitude 47 degrees 46 minutes 24 seconds N, Longitude 119 degrees 18 minutes 57 seconds W)

RANGE IN CHARACTERISTICS: The mean annual soil temperature is 49 to 51 degrees F. These soils are usually moist in the moisture control section but are dry for 90 to 105 consecutive days following the summer solstice. The upper part of the particle-size control section has estimated moist bulk density of 1.10 to 1.35 g/cc, volcanic glass content of 30 to 60 percent, including 10 to 20 percent sand-size ash, 0.5 to 2.0 mm.in diameter, acid-oxalate extractable aluminum plus one-half of the acid-oxalate extractable iron of 0.15 to 0.40 percent, 15-bar water retention of 5 to 10 percent, 3 to 15 percent rock fragments, and an apparent field estimated clay content of 3 to 12 percent. The lower part of the control section has 5 to 30 percent volcanic glass, 15 to 35 rock fragments and 5 to 10 percent clay content. Depth to secondary carbonates is 15 to 30 inches. Depth to a weakly to moderately cemented duripan is 20 to 40 inches. Depth to dense glacial till is 24 to 44 inches. Depth to basalt is 40 to over 60 inches. The mollic epipedon is 10 to 30 inches thick. Thickness of the volcanic ash influence is 14 to 30 inches.

The Ap horizon has a value of 4 or 5 dry and 2 or 3 moist. The chroma is 2 or 3 dry or moist.

The A horizon has a value of 4 or 5 dry and 2 or 3 moist. Chroma is 2 or 3 dry or moist. Texture is ashy fine sandy loam, ashy loam or ashy sandy loam. Neutral to slightly alkaline.

The AB horizon has a hue of 10YR or 5Y. The value is 3 or 4 moist. The chroma is 2 or 3 dry or moist. Texture is gravelly or cobbly ashy sandy loam, gravelly ashy fine sandy loam, gravelly ashy loam or very cobbly ashy sandy loam. Neutral to moderately alkaline.

The 2Bk horizon has a hue of 2.5Y, 5Y or 10YR. A value of 5 or 6 dry and 3 or 4 moist. The chroma is 1 to 4 dry and 2 or 3 moist. Textures are gravelly loam, fine sandy loam or sandy loam that may be cobbly or very cobbly. Neutral to moderately alkaline.

The 2Bkqm horizon has a hue of 2.5Y or 5Y. A value of 5 or 6 dry and 2 to 4 moist. The chroma is 1 or 2 dry or moist. The cemented duripan crushes to gravelly, cobbly or very cobbly sandy loam or very gravelly loam. Slightly to strongly alkaline.

The 2Cdk horizon has a hue of 5Y or 2.5Y. A value of 5 or 6 dry and 3 or 4 moist. Chroma is 1 or 2 dry or moist. Texture is cobbly or very cobbly sandy loam. Slightly to moderately alkaline.

COMPETING SERIES: There are no competing series.

GEOGRAPHIC SETTING: Siweeka soils are on till plains on glaciated plateaus with slopes of 0 to 65 percent. These soils formed in loess and volcanic glass over glacial till.

Elevations are 1,300 to 3,200 feet. Average annual precipitation is 11 to 15 inches. Average January temperature is about 26 degrees F. and average July temperature is about 70 degrees F. Average annual temperature is 47 to 50 degrees F. Frost-free season is 110 to 170 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Alecanyon, Argabak, Brazlan, Nemire, Stubblefield and Timentwa series. The Alecanyon soils are in outwash channels or eskers and are sandy-skeletal. Argabak soils are on nearly level to gently sloping summits or strongly sloping and steep upland shoulders adjacent to outcrops and are shallow to bedrock. Brazlan soils are on mounds. Timentwa soils are on till plains but lack a duripan within 40 inches. Stubblefield soils are on uplands and have less ash. Nemire soils are in channels and lack a duripan.

DRAINAGE AND PERMEABILITY: Well drained, very slow to rapid runoff; moderately rapid permeability.

USE AND VEGETATION: Dryland cropland with some used for livestock grazing. Crops are wheat and barley. Potential native vegetation is includes bluebunch wheatgrass, Idaho fescue, threetip sagebrush and Wyoming big sagebrush.

DISTRIBUTION AND EXTENT: Douglas County, Washington. Series is of moderate extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Portland, Oregon

SERIES ESTABLISHED: Douglas County, Washington, 1998.

REMARKS: Diagnostic horizons and features recognized in this pedon are a mollic epipedon from the surface to 27 inches, and a weakly cemented duripan at 36 inches. The particle size control section is the zone from 10 to 36 inches.

ADDITIONAL DATA: Partial lab data is available from Lincoln, Nebraska. NSSL pedon number 90P0336.

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APPENDIX B

TOUHEY SOIL MAP UNIT DESCRIPTION (428)

TOUHEY SERIES

The Touhey series consists of moderately deep to weakly cemented duripan, well drained soils formed in glacial till mixed with volcanic ash and loess. Touhey soils are on side slopes and toe slopes of undulating till plains on plateaus. Slopes are 0 to 65 percent. Average annual precipitation is about 10 inches and average annual temperature is 49 degrees F.

TAXONOMIC CLASS: Ashy over loamy, glassy over mixed, superactive, mesic Vitritorrandic Durixerolls

TYPICAL PEDON: Touhey fine sandy loam - cropland, on a 1 percent slope at an elevation of 2,250 feet. (Colors are for dry soil unless otherwise stated. All textures are apparent field textures.)

Ap--0 to 5 inches; grayish brown (10YR 5/2) fine sandy loam, very dark grayish brown (10YR 3/2) moist; moderate fine granular structure; soft, very friable, nonsticky and nonplastic; common very fine and fine roots; few very fine interstitial pores; 5 percent pebbles; 3 percent sand-size pumice, 0.5 to 2.0 mm. in diameter; neutral (pH 7.0); abrupt wavy boundary. (4 to 10 inches thick)

A--5 to 12 inches; brown (10YR 5/3) fine sandy loam, very dark grayish brown (10YR 3/2) moist; weak medium subangular blocky structure; soft, very friable, nonsticky and nonplastic; common very fine roots; common very fine and fine interstitial pores; 10 percent pebbles; 3 percent sand-size pumice, 0.5 to 2.0 mm. in diameter; neutral (pH 7.2); clear wavy boundary. (6 to 9 inches thick)

Bw1--12 to 21 inches; yellowish brown (10YR 5/4) gravelly fine sandy loam, dark brown (10YR 3/3) moist; weak medium subangular blocky structure; soft, very friable, nonsticky and nonplastic; common very fine roots; common very fine and fine interstitial pores; 20 percent pebbles and 5 percent cobbles; 3 percent sand-size pumice, 0.5 to 2.0 mm. in diameter; slightly alkaline (pH 7.4); clear wavy boundary. (5 to 10 inches thick)

Bw2--21 to 30 inches; pale brown (10YR 6/3) gravelly sandy loam, dark brown (10YR 3/3) moist; weak, fine subangular blocky structure; soft, very friable, nonsticky and nonplastic; common very fine roots; common very fine and fine interstitial and tubular pores; 20 percent pebbles and 10 percent cobbles; slightly alkaline (pH 7.8); clear wavy boundary. (8 to 10 inches thick)

2Bk--30 to 38 inches; light gray (10YR 7/2) gravelly sandy loam, gray brown (2.5Y 5/2) moist; massive; hard, firm, nonsticky and nonplastic; common very fine roots; few very fine tubular pores; 25 percent pebbles, 5 percent cobbles and 3 percent stones; few fine lime filaments and threads; violently effervescent; strongly alkaline (pH 8.6); abrupt wavy boundary. (6 to 10 inches thicks)

2Bkqm--38 to 40 inches; olive brown (7.5 YR 4/4), weakly cemented duripan that crushes to very gravelly sandy loam, white (10YR 8/2) and olive brown (2.5Y 4/2) moist; massive; very hard, very firm, nonsticky and nonplastic; few very fine roots; few very fine tubular pores; 35 percent pebbles and 5 percent cobbles; common medium lime filaments; violently effervescent; strongly alkaline (pH 8.6); gradual wavy boundary. (1 to 4 inches thick)

2Cdk--40 to 60 inches; dense lodgement till, olive brown (2.5Y 4/2) very gravelly sandy loam, light brownish gray (2.5Y 6/2) moist; massive; hard, firm, nonsticky and nonplastic; few very fine roots; few fine tubular and interstitial pores; 35 percent pebbles, 5 percent cobbles and 5 percent stones; few thin lime filaments; strongly effervescent; moderately alkaline (pH 8.4).

TYPE LOCATION: Douglas County, Washington, about 3/4 miles southeast of Mansfield; 800 feet west and 1,300 feet north of the southeast corner section 25, T.27N., R.25 E.

(Latitude 47 degrees 48' 18"N, Longitude 119 degrees 37' 19"W)

RANGE IN CHARACTERISTICS: The mean annual soil temperature is 50 to 53 degrees F. These soils are dry in the moisture control section for one-half to three-fourths of the time when the soil temperature is above 41 degrees F. The mollic epipedon is 10 to 19 inches thick. Organic carbon is less than 0.60 percent at 20 inches. The upper 5 to 14 inches of the 10 to 40 inch particle-size control section has moist bulk density of 1.10 to 1.50 g/cc, 30 to 60 percent volcanic glass content, including 3 to 10 percent sand-size pumice, 0.5 to 2.0 mm. in diameter, acid-oxalate extractable aluminum plus one-half of the acid-oxalate extractable iron of 0.15 to 0.40 percent, P-retention of 9 to 15 percent, 15-bar water retention of 3 to 8 percent for air dried samples, 3 to 12 percent rock fragments, and an apparent field estimated clay content of 5 to 12 percent. The lower part of the control section to 40 inches has less than 30 percent volcanic glass, 20 to 35 rock fragments and 6 to 12 percent clay content. Depth to a weakly to moderately cemented duripan is 20 to 40 inches and it is underlain by dense glacial till. Depth to basalt bedrock is 40 to more than 60 inches.

The Ap horizon has chroma of 2 or 3 moist. It has 5 to 10 percent pebbles and is moderately acid to slightly alkaline.

The A horizon has chroma of 2 or 3 dry or moist. It has 5 to 15 percent pebbles and is neutral or slightly alkaline. Textures are fine sandy loam or very fine sandy loam.

The Bw1 horizon has value of 4 or 5 dry. Chroma is 2 through 4 moist or dry. Textures are fine sandy loam, loam or very fine sandy loam and has 10 to 25 percent rock fragments.

The Bw2 horizon has value of 4 to 6 when dry and 3 to 5 moist. Chroma is 1 to 4 dry or moist. Textures are fine sandy loam, sandy loam, very fine sandy loam or loam and has 20 to 35 percent rock fragments.

The 2Bk horizon has hues of 2.5Y or 10YR. Value is 5 to 7 dry and 3 to 5 moist. Chroma is 1 or 2 dry or moist. Textures are sandy loam, fine sandy loam, or loam and has 20 to 35 percent rock fragments. Reaction is slightly to strongly alkaline.

The 2Bkqm horizon has hue of 7.5YR, 10YR, or 2.5YR. Value is 4 to 8 dry and 4 or 5 moist. Chroma is 1 to 4 dry or moist. Textures are fine sandy loam or sandy loam and contains 20 to 35 percent rock fragments. Duripan is weakly or moderately cemented.

The 2Cdk horizon has hue of 2.5Y or 10YR. Value is 5 to 7 dry and 4 or 5 moist. Chroma is 1 or 2 dry or moist. Textures are sandy loam, loam or fine sandy loam and contains 25 to 45 percent rock fragments. Reaction is moderately or strongly alkaline.

Basalt bedrock occurs below the 2Cdk layer at depths of 40 to 60 inches in some pedons.

COMPETING SERIES: This is the Simsfield (T) series. The Simsfield (T) series has 2 to 5 percent coarse fragments throughout the soil profile.

GEOGRAPHIC SETTING: Touhey soils formed in ablation glacial till mixed with volcanic ash, pumice and loess in the surface over dense lodgement till on side slopes and toe slopes on plateaus. Elevations are 1,200 to 2,800 feet. Slopes are 0 to 65 percent. The climate is semiarid with warm, dry summers and cool, moist winters. Average annual precipitation ranges from 9 to 12 inches. Average July temperature is 71 degrees F.; average January temperature is 27 degrees F. and average annual temperature is 48 to 51 degrees F. Frost-free season is about 130 to 185 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the DelRio, Heytou, Stubblefield, Strat, and Tagear soils. DelRio soils are in low positions and are deep. Heytou soils are on till plains and are skeletal and lack a duripan. Stubblefield soils are on till plains and have over 35 percent rock fragments. Strat soils are on outwash plains and lack a duripan and have over 35 percent rock fragments. Tagear soils are on till plains and have a duripan below 40 inches.

DRAINAGE AND PERMEABILITY: Well drained, very slow to rapid runoff; moderately rapid permeability above the duripan.

USE AND VEGETATION: Touhey soils are used mostly for dryland wheat and barley production with a small amount used for livestock grazing and irrigated orchards. Vegetation is bluebunch wheatgrass, Wyoming big sagebrush, Sandberg bluegrass and needleandthread. The cool phase vegetation is Idaho fescue, threetip sagebrush, Sandberg bluegrass and needleandthread.

DISTRIBUTION AND EXTENT: North Central Washington. The soils are extensive.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Portland, Oregon

SERIES ESTABLISHED: Douglas County, Washington, 1942.

REMARKS: Diagnostic horizons and features recognized in this pedon are a mollic epipedon from the surface to 12 inches, a cambic horizon from 12 to 30 inches, a zone of carbonate accumulation from 30 to 38 inches, and a weakly cemented duripan from 38 to 40 inches. Dense lodgement till occurs from 40 to 60 inches. The upper 21 inches of the profile has an estimated 30 to 60 percent volcanic glass content (see additional data). The particle-size control section is the zone from 10 to 38 inches (the lower part of the A and the Bw1, Bw2 and the 2Bk horizons).

ADDITIONAL DATA: Complete NSSL lab characterization data is available under another pedon number 90P1011. Glass grain counts are COSI = 6 and VFS = 19, estimated glass content are FS = 19 and with pumice in the profile coarse ash is estimated to be 95 percent of MS, CS, VCS fraction. Calculated glass content is 45 percent of the 0.02 to 2mm fraction.

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