THESIS

PEDOGENIC CONTROLS ON NITRATE LEACHING IN CULTURED COLORADO SOILS

Submitted by

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ABSTRACT

PEDOGENIC CONTROLS ON NITRATE LEACHING IN CULTURED COLORADO SOILS

Nitrate leaching from irrigated agriculture remains a major driver of groundwater contamination and non-point source pollution in semi-arid regions of Colorado. While management practices influence nutrient dynamics, this study demonstrates that pedogenic soil properties exert the dominant control on nitrate mobility and retention. Through detailed pedon characterization and integration of long-term deep nitrate data from the South Platte Basin (10 years) and short-term data from the Arkansas Basin (2 years), we applied Principal Component Analysis (PCA), linear mixed-effects modeling, and segmented regression threshold analysis to identify soil properties governing nitrate behavior across contrasting pedogenic settings. Results indicate that total calcium carbonate ($CaCO_3$), total nitrogen (TN), and clay content are the most influential predictors of nitrate concentration in the South Platte Basin, where finer-textured soils and stronger horizon development constrain nitrate mobility. Clay distribution and total nitrogen near the site mean represented the threshold point where nitrate persistence increased more dramatically, while elevated carbonate levels restricted vertical percolation, promoting lateral flow and retention within the profile. In contrast, the Arkansas Basin model showed no statistically significant linkages, likely reflecting both the limited two-year dataset and weaker pedogenic development in its coarser parent materials. These findings underscore that nitrate leaching potential in the South Platte Basin’s furrow-irrigated systems is governed by the interaction between nutrient availability and soil hydrologic architecture rather than by management alone. Fertilizer management dictates the quantity of nitrate at risk for transport, but the subsurface structure, shaped by clay illuviation, carbonate accumulation, and horizon continuity, ultimately determines its fate. Pedologically informed nutrient and irrigation management, supported by long-term datasets and site-specific monitoring, is essential to improving nitrogen use efficiency and protecting groundwater quality in Colorado’s irrigated agroecosystems.

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CHAPTER 1: INTRODUCTION AND METHODS

1. INTRODUCTION

Soils are a vital component of the Earth’s critical zone, supporting human activities and both cultivated and natural ecosystems. They function as open systems that exchange energy and matter with their environment. Soils are the result of an alteration of parent materials by pedogenic processes. Pedogenic processes result in temporal and spatial variation among soil properties vertically and result in the differentiation of soil horizons. These dynamic interactions can be categorized into internal and external processes that add, lose, translocate, and transform matter (Simonson 1959). When humans interact with the soil system, the rates of soil formation are altered. The variation in the rates of soil-forming processes are reflected in the chemical, physical, and morphological properties of the soil. Spatial and temporal variations driven by natural and anthropogenic influences can serve as proxies to identify which properties control leaching potential.

In agricultural systems, fertilizers are essential to sustaining the exchange of matter and energy within the soil environment and maintaining the equilibrium required for global food security. Among these inputs, nitrogen fertilizer represents one of the most significant and consistent sources of both additions and losses in the soil system (Amundson et al., 2015).

Soils that are uncultivated (native soils) express different properties than similar soils influenced by agricultural management practices. Generally, most agricultural soils in furrow-irrigated systems exhibit truncated profiles due to surface erosion, resulting in significant sediment loss from the system. As a result, the total amounts of properties such as total nitrogen and total carbon are reduced in the pedon. The loss of sediment from the surface in agricultural soils, particularly under furrow irrigation, also brings endopedons, such as argillic horizons, closer to the surface. In many cultivated systems, these soil properties have been altered by erosion processes and replaced by subsurface carbonate-rich soil layers. These soil morphological properties can be used to identify properties that regulate water movement and, therefore, degrees of leaching potential.

Agriculture occupies about 45% of Earth's habitable land. In comparison, arid and semi-arid regions cover roughly 41% of terrestrial surfaces and support more than one-third of the global population (Golla, 2021), underscoring their essential role in sustaining human society. While nitrogen fertilizers are essential to maintain agricultural productivity and global food security, their excessive use leads to nitrate runoff that adversely impacts water quality and ecosystem health.

In North America, 80% of the central grasslands have been converted to cropland (Foley et al., 2005), and statewide assessments have identified agricultural non-point source (NPS) pollution as the primary cause of declining water quality. (U.S Environmental Protection Agency [EPA], 2016). Balancing agricultural production with environmental protection requires developing a quantitative understanding of soil properties and their influence on nitrogen fate and mobility in agricultural landscapes.

The Haber-Bosch process has increased global nitrogen fertilizer use by 800% over the last 100 years (Govindasamy et al., 2023). Responsible for over 96% of the planetary ammonia production, the process has enabled increases in food production. These production increases have created new and sustained environmental impacts. Currently, approximately 150 million tons of ammonia are produced annually, with 70–80% used in production agriculture. It has been estimated that 50% of applied nitrogen fertilizer is taken up by crops, while the rest is lost through processes such as volatilization, nitrous oxide emissions, and leaching through the soil profile (Ritchie et al., 2022; Govindasamy et al., 2023).

In Colorado, agricultural land (including rangeland and pasture) encompasses nearly half of the state's land area. Irrigated croplands cover about 16%(Colorado Department of Agriculture et al., 2000). Much of this cultivation is concentrated in the South Platte and Arkansas River Basins, where nutrient runoff creates water quality challenges. The state's NPS Program, supported by the EPA under the Clean Water Act, addresses this issue through targeted, voluntary efforts guided by Regulation 85 (CDPHE 2023). Understanding and determining fundamental pedogenic controls driving N leaching is therefore essential to protecting Colorado's water resources, an urgent need this thesis aims to address.

The South Platte and Arkansas basins display contrasting pedogenic settings that shape likely hydrologic behavior and the fate and mobility of nitrate in soils. Typical parent materials in the South Platte region are derived from alluvial deposits of sandstone and shale (Kelly et al., 2008; Soil Survey Staff, 2017).

In the Arkansas Basin, typical parent material is derived from Quaternary alluvium and eolian deposits of loess, silt, and sand, as well as Cretaceous shale, limestone, and sandstone (Chapman et al., 2006). The resulting soil system is characterized by coarser textures than those of the South Platte Basin. Here, soils express stronger carbonate and gypsum accumulation.

Both geographic locations in Colorado exist within semi-arid soil moisture regimes and receive approximately 300–350 mm of rainfall annually. These contrasting soil systems provide an effective framework for examining how pedogenic variability governs nitrate retention and leaching potential across Colorado's irrigated agroecosystems.

Nitrogen management in agricultural soils has gained renewed attention due to its significant impact on greenhouse gas emissions and water quality. Nitrogen in soils exists in organic and inorganic forms that make up the Total nitrogen pool. e. The organic nitrogen pool is not directly available to plants and is mineralized into inorganic forms (e.g., ammonium), which plants then utilize. Inorganic forms such as Ammonium can be further converted into nitrate, which is very mobile and easily utilized by plants, but is also highly prone to leaching due to its higher solubility in water. Nitrate (NO_3^-) also carries a negative charge and therefore has low adsorption onto positively charged soil surfaces. Because nitrate is highly soluble and weakly retained in soil, it is particularly susceptible to leaching from agricultural systems. As a result, these losses reduce nitrogen use efficiency and contribute to groundwater contamination and eutrophication in downstream ecosystems (Rupert, 2008; Shukla & Saxena, 2020).

In recent years, there has been a growing focus on evaluating and enhancing nitrogen use efficiency (NUE) in agricultural systems. Currently, the global average NUE does not exceed 50%, falling short of the estimated 67% needed to meet future food demand while maintaining acceptable air and water quality (Prud’homme, 2005). This renewed interest in nitrogen management arises from the urgent need to balance crop productivity with environmental sustainability. Understanding the processes governing nitrate leaching, along with the physical, chemical, and biological soil properties that influence them, is essential for assessing impacts on ecosystem structure and function.

Investigations into soil management practices have shown they can significantly influence nitrate dynamics by altering soil physicochemical and biological properties, thereby affecting nitrate retention and mobility (Diaz et al., 1994; Smith, 2001; Morgan et al., 2021). Consequently, a thorough examination of these soil management practices will provide insight into the mechanisms by which nitrate leaching can be controlled within various agricultural settings. This work pairs a wide range of pedological data with statistical tools, including PCA, mixed-effects multivariate modeling, and sensitivity analysis, to identify the key soil properties governing nitrate leaching in cultivated Colorado soils and to provide a comprehensive analysis of how agricultural practices influence nitrate dynamics.

A substantial body of agricultural research has employed linear mixed-effects models (lmer) and repeated measures approaches to address spatial and temporal dependencies in soil datasets (e.g., Gilliam & Adams, 2011; Schuster et al., 2022). These models account for variability across locations and times, allowing for more accurate inference of the effects of soil properties, such as pH, organic matter, texture, and structure, on nitrate dynamics. Compared to traditional regression models, lmer models offer greater precision when analyzing repeated measurements across sites or time points. To complement this, we integrated Principal Components Analysis (PCA), a widely used dimensionality reduction technique, to help identify key input variables for the mixed-effects models. PCA works by transforming a set of correlated variables into a new set of uncorrelated components, thus revealing the most informative variables while minimizing redundancy (Kyriazos & Poga, 2023).

1.1 LITERATURE REVIEW

Native shortgrass steppe soils are characterized by high surface-horizon organic matter, with 90% of root mass concentrated in the top 20 cm. These soils have dark surface horizons with 1–3% organic carbon and maintain high base saturation and pH due to limited leaching under semiarid conditions. Subsurface horizons often contain secondary accumulations of calcium carbonate and clay that reflect long-term wetting-front dynamics. Soil variability across the steppe is primarily driven by fine-scale differences in parent material, soil age, and microtopography (Kelly et al., 2008). Yet in agricultural soils, the region’s dry climate makes irrigation essential to sustain production.

According to the 2023 *Irrigation and Water Management Survey* (IWMS), Colorado contains 12,764 irrigating farms that collectively manage approximately 2.37 million irrigated acres. Irrigation in the state is divided primarily between gravity-fed systems and sprinkler-based systems. Gravity systems remain the most widely used, with 76.9% of irrigating farms reporting them and 1,121,454 acres, or 47.4% of the state’s irrigated land, being irrigated with them. Within this category, down‑furrow irrigation continues to play a central role: 4,528 farms reported using furrow methods across 446,773 acres, representing 46% of gravity‑irrigating farms, 40% of gravity‑irrigated acreage, and roughly 19% of all irrigated acres statewide. Sprinkler irrigation is used by 32.5% of irrigating farms and covers 1,289,171 acres (54.5% of irrigated land), with center pivot systems overwhelmingly dominant. Center pivots were reported by 2,284 farms and account for 1,200,630 acres, approximately 90% of sprinkler‑irrigated acreage and just over half (50.7%) of all irrigated acres in Colorado. Drip and microirrigation systems remain comparatively uncommon, used by only 6.9% of farms and applied to less than 1% of irrigated acreage. Overall, Colorado’s irrigated agriculture reflects a near‑even distribution between gravity‑fed and sprinkler systems, with furrow irrigation continuing to represent a substantial share of the state’s surface‑irrigated acreage (USDA - NASS, 2023 IWMS).

Conservation tillage practices remain uncommon in these furrow-irrigated systems. The combination of intensive crop management and irrigation, particularly in the absence of conservation practices, can have profound impacts on soil morphological, chemical, and physical properties and accelerate the degradation of critical soil attributes that regulate nitrogen movement, increasing the risk of both surface and groundwater contamination (Bauder et al., 2018; Blecker et al., 2009).

Furrow irrigation is often applied in pulses, with large volumes of water flowing down furrows. Under fallow conditions, infiltration and wetting uniformity are often uneven and unregulated with furrow irrigation. Potentially resulting in increased sediment loss and leaching. Other irrigation practices common in Colorado, like sprinkler or drip irrigation, apply water more precisely and minimize the risk of deep percolation and nutrient loss.

Furrow irrigation infiltration patterns depend heavily on the amount of surface residue and soil properties. In general, however, fast inflow results in increased runoff (sediment and nutrient loss) while slow inflow increases the system's leaching potential. Excess residue in the furrow slows water advance time, increases infiltration, and increases the wetted perimeter, thereby increasing nitrate leaching potential. It has also been found that increasing surface residue reduces sedimentation loss (Wardle et al., 2015). One method that has been studied as a remedy for the resulting hydrologic impacts of increased surface residue is irrigating every other furrow. This has been shown to increase lateral flow, thereby reducing potential for leaching and runoff while also reducing net water applied to the system (Lehrsch et al., 2001).

In Colorado's agricultural ecosystems, our understanding of how specific soil properties influence nitrate leaching is growing but remains incomplete, particularly at finer spatial scales. Well-documented factors contributing to leaching risk include soil texture, where sandy soils leach more readily due to lower water-holding capacity and higher permeability, as well as drainage class and slope, which affect water movement through the profile (Strock et al., 2002; Gates et al., 2008). Shallow water tables limit the soil's ability to retain nitrate, increasing the risk of leaching. At the same time, higher organic matter can either enhance nitrogen retention through microbial immobilization or increase nitrate availability via mineralization (Rupert, 2008). Although cation exchange sites do not hold nitrate, soils with higher cation exchange capacity (CEC), often associated with greater clay or organic matter content, can indirectly reduce leaching by slowing water movement (Bauder et al., 2011). However, gaps in understanding remain, particularly regarding in depth pedological comparisons throughout the whole soil profile across a wide range of soil property data, the role of soil structure and preferential flow (e.g., through root channels or macropores), and how management practices, such as tillage, irrigation, and fertilizer placement, interact with soil characteristics to influence nitrate transport (Gates et al., 2008; O'Neill et al., 2010). Seasonal dynamics further complicate prediction, as shifts in moisture, microbial activity, and plant uptake influence leaching risk over time. Current research efforts are addressing these challenges through methods such as coupling soil survey data with hydrologic modeling and field monitoring tools (e.g., suction lysimeters), employing precision agriculture technologies to detect within-field variability, and using tracer studies and isotope analyses to trace nitrate sources and movement (Rupert, 2008; Bauder et al., 2011). As a result, studies like this contribute to an emerging body of site-specific knowledge that integrates pedology, hydrology, and management to better understand and predict nitrate leaching in Colorado soils.

The addition of synthetic fertilizers for agricultural purposes increases total nitrogen (TN) levels in the soil system and may lead to accumulating nitrogen concentrations within the soil profile (Wang et al., 2020). Through the microbial-mediated process of nitrification, ammonium (a common nitrogen-based fertilizer) is converted to nitrate, which is highly water-soluble in soils (Beeckman et al., 2018). This nitrate can persist in shallow groundwater for years, posing long-term environmental concerns (Noland et al., 2002).

Given that water serves as a master variable in terrestrial ecosystems, the interaction between soil and hydrology fundamentally governs solute movement and biogeochemical cycling across spatial and temporal scales. Hydrological soil dynamics determine the partitioning of water among surface runoff, root zone storage, lateral flow, and deep percolation into groundwater. Consequently, soil hydrology is a critical bottleneck in nitrate transport through the soil profile and at the scale.

Soil hydrological dynamics determine how water is partitioned among surface runoff, root zone storage, lateral flow, and deep percolation into groundwater. This partitioning directly impacts nitrogen loss in its various forms, including leaching (Jia et al., 2007). Runoff generation mechanisms are commonly classified into four dominant categories: Hortonian overland flow (infiltration excess), saturation overland flow (saturation excess), lateral subsurface flow, and deep percolation contributing to groundwater recharge. Among these, subsurface lateral flow has been widely recognized as a preferential pathway for nitrate transport (Jia et al., 2007, p.90).

Soil is a hydrologically active medium where water movement is not uniform but highly regulated by a complex interplay between biotic and abiotic properties. These properties regulate water movement and, consequently, nitrate leaching through mechanisms such as preferential flow, capillary action, and aggregate stability. Preferential flow is the uneven and rapid movement of water and solutes through specific pathways in the soil, bypassing the surrounding soil matrix (Lin 2012).

Soil structure and aggregation play a fundamental role in regulating water flow through the soil profile. Macro- and micro-aggregates, formed through biological activity (e.g., fungi, roots, microbes) and the presence of soil organic matter (SOM), create a hierarchical structure that governs water infiltration and retention. Well-developed aggregation increases porosity and enhances water conductivity, whereas poor structure can impede water flow, leading to surface runoff and ponding (Lin, 2012).

The size and distribution of pores in soil (e.g., pore network characteristics) are another critical property influencing water movement and, by extension, nitrate leaching. Macropores originating from root channels and other forms of bioturbation facilitate preferential flow that bypasses the soil matrix, potentially leading to rapid leaching of solutes such as nitrate. In contrast, micropores retain water for plant uptake but restrict infiltration rates. A mixed pore-size distribution, in which large pores are embedded within a fine-textured matrix, often leads to non-equilibrium flow conditions, characterized by differences in water content and pressure across pore domains.

Soil texture and mineralogy are additional key drivers of water flow dynamics. Clay-rich soil typically has high water-holding capacity but low infiltration rates, often resulting in the formation of perched water tables. Sandy soil, on the other hand, allows for rapid percolation but has low water retention, thereby increasing the risk of leaching. Contrasting textures within and among soil horizons may further impede vertical flow and instead promote lateral water movement.

Soil organic matter (SOM) enhances water regulation directly by absorption and indirectly by promoting aggregation, increasing porosity, and water holding capacity. It also stimulates microbial activity, which can further modify the soil's physical structure through decomposition and bioturbation processes.

Restrictive horizons such as fragipans, petrocalcic layers, or lamellae act as physical barriers to water movement. These features may lead to the development of perched water tables or encourage lateral subsurface flow, particularly under saturated conditions.

Biological factors also exert significant control over soil water dynamics. Root systems influence the formation and continuity of macropores, thereby affecting both water uptake and transport pathways. Additionally, soil fauna (e.g., earthworms, insects) enhance vertical and horizontal water movement through bioturbation, thereby facilitating nitrate transport (Lin 2012). Together, these soil properties determine how much water infiltrates the soil, where and how it moves, how long it is retained, and ultimately, how deeply solutes like nitrate are leached through the profile.

Reducing nitrogen loss from agricultural systems to the surrounding environment has been a longstanding challenge for the agricultural industry (Huang et el., 2024). Management practices in agriculture significantly alter soil physical structure and hydrologic behavior. Furthermore, land stewardship practices such as conservation tillage, which involves less soil disturbance than conventional tillage, are expected to affect soil properties, thereby driving nitrate leaching in agricultural systems. For instance, conventional tillage (CT) disrupts soil aggregates through mechanical disturbance, reducing macro and microaggregate stability, therefore increasing bulk density over time and breaking the vertical continuity of pores. Conservation tillage practices such as strip tillage (ST), in which only narrow strips of soil are tilled to prepare a seedbed while the soil between strips remains undisturbed, help preserve pedogenically driven aggregate integrity by minimizing soil disturbance and promoting SOM accumulation, which supports biological aggregate stabilization through fungal hyphae, root exudates, and microbial metabolites (Huang et al., 2024).

Tillage management may also impact hydropedology via pore networks and preferential flow pathways. Hydropedology is the study of the formation, distribution, and function of soils as they interact with water in the vadose zone (the unsaturated zone between the land surface and groundwater), emphasizing how soil morphology, structure, and properties regulate water movement, storage, and fluxes (Lin, 2012). Conventional tillage often leads to a more homogenized pore system near the surface but reduces the continuity of macropore networks by severing root channels and disrupting worm burrows (Lin 2012). This can create shallow compaction (plow pan) that acts as a restrictive horizon, causing perched water or lateral flow.

Conservation tillage allows persistent biopore development (root channels, worm burrows, soil cracking) to remain intact, which favors preferential flow. This can enable nitrates to bypass the matrix and rapidly leach through macropores, especially during high-intensity rainfall or irrigation. Conservation tillage tends to increase vertical water movement but may also increase the risk of nitrate leaching via preferential pathways, unless mitigated by strategies such as cover cropping. Conventional tillage may reduce deep leaching but increase runoff losses and shallow pooling above compacted layers (Huang et al., 2024 & Purdue University Extension, 1994).

Although changes in soil texture over time do not result from tillage operations, texture itself remains a significant driver of water movement in soils and, consequently, of nitrate leaching risk. In sandy soil, both tillage systems are vulnerable to leaching due to the inherent rapid drainage. However, conventional tillage further reduces SOM and structure, worsening retention. Conservation tillage enhances water retention through organic matter buildup and better aggregation, offering modest buffering.

In clay-rich soils, conventional tillage is particularly effective at increasing infiltration rates and improving drainage through improved aggregation and biopores. However, it often exacerbates perched water table formation due to compaction and poor structure. Conventional tillage moderates texture extremes by buffering rapid flow in sandy soils and improving infiltration in clay soils. But in both cases, preferential flow risk increases with the presence of intact macropores (Zhou et al., 2022).

Tillage practices also influence the formation of restrictive horizons. Intensive plowing in conventional tilled systems is known to compact the subsurface over time, increasing bulk density and reducing permeability. These plow pans act as hydraulic barriers, promoting lateral flow or perched saturation zones. Although some literature suggests that conservation tillage may encourage biological processes that alleviate compaction and promote aggregation, evidence shows that conventional tillage frequently exacerbates subsurface restriction rather than alleviating it (Purdue University Extension, 1994; Li et al., 2024).

Hydrological properties that influence nitrate leaching risk, such as pore structure, flow dynamics, and soil retention characteristics, are shaped by tillage practices, with long-term effects that are complex and difficult to predict. To unpack these interactions, statistical tools such as Principal Components Analysis (PCA), multivariate linear regression (e.g., linear mixed models), and sensitivity analysis can be applied to: (1) identify which soil properties explain the most variation in nitrate concentration; (2) use those insights to develop predictive models of nitrate concentration by depth; and (3) simulate scenarios where a one standard deviation change in a given soil property produces a quantifiable change in nitrate levels. This approach helps reveal the key drivers of nitrate dynamics in Colorado agricultural systems.

The Colorado State University Agricultural Water Quality Program (AWQP) is a collaborative initiative supporting statewide water quality research. It brings together teams from Colorado State University (CSU), the Colorado Department of Agriculture, and the Colorado Department of Public Health and Environment. CSU's role focuses on research, education, and training related to agricultural Best Management Practices (BMPs), with an emphasis on reducing the impacts of fertilizer and pesticide use on drinking water sources, a focus closely related to the goals of this work. The AWQP has collected historical deep soil nitrate samples from each of the study sites included in this research. These data, combined with pedological data collected and analyzed by our team, form the foundation of the analyses presented in this thesis.

1.2 RESEARCH OBJECTIVES

This study aims to investigate two key areas. 1) Identify key soil properties that serve as pedologic proxies for nitrate leaching in Colorado agricultural soils across two watersheds at the field scale, and 2) Assess and compare conservation vs conventional tillage influences on leaching potential across basins.

1.3 SITE SELECTION

The sites for this research were selected from two Colorado watersheds: the South Platte Basin and the Arkansas Basin (Figures 1.1 and 1.2). In the South Platte River Basin, research was conducted at two sites located in northeastern Colorado along the Front Range, approximately 20 miles south of the Wyoming border. These included a native grassland site (N1) and a nearby cultivated site (CU1). In the Arkansas River Basin, two additional sites were studied in southeastern Colorado, located roughly 80 miles north of the New Mexico border and 90 miles west of the Kansas border. These included a native grassland site (N2) and a cultivated site (CU2).

Comparing the South Platte and Arkansas River Basins is crucial for understanding nitrate contamination risks because, although both are agriculturally intensive watersheds in Colorado with semi-arid climates and similar topography, they differ in water-use patterns, dominant cropping systems, and water-quality challenges. The South Platte River Basin has widespread nitrate contamination from fertilizer, livestock operations, and urban runoff, reflected in higher rates (35.7%) of groundwater samples exceeding the EPA's nitrate maximum contaminant level (MCL) of 10 ppm, with some wells showing concentrations over 250 ppm (Bauder et al., 2012). In contrast, the Arkansas River Basin exhibits lower overall nitrate exceedance rates (16.7%), but still faces significant nutrient runoff from agriculture, compounded by salinity and selenium issues. These contrasting yet overlapping challenges make the two basins valuable comparative systems for evaluating how land use, irrigation practices, and soil dynamics influence nitrate leaching risks and groundwater vulnerability across Colorado's agricultural regions (Colorado Department of Agriculture, 2016). The distinct soil-forming characteristics of these sites are presented in Table 1.1.

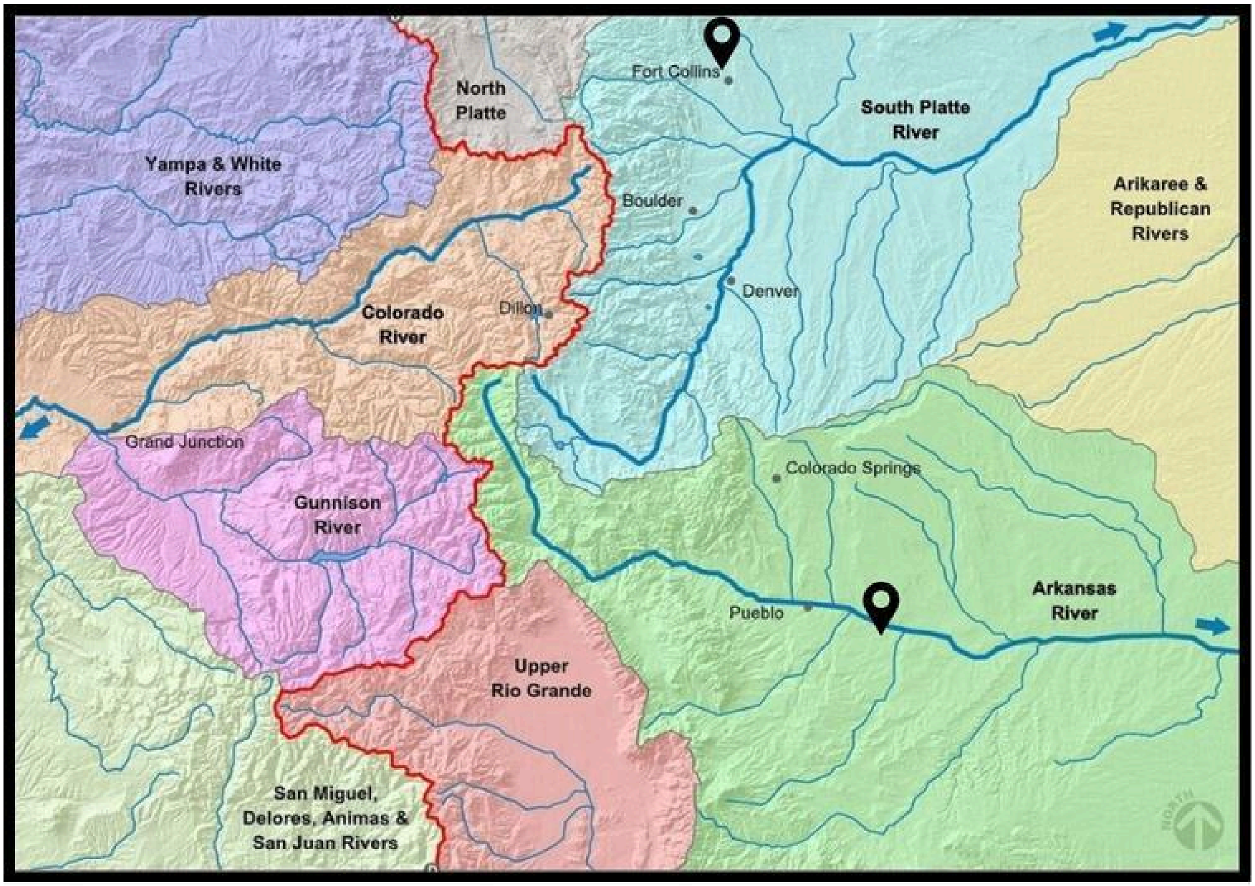


Figure 1.1. Site locations in Colorado in relation to watershed boundaries. *Image source: Southwick Associates and Colorado Department of Natural Resources.*

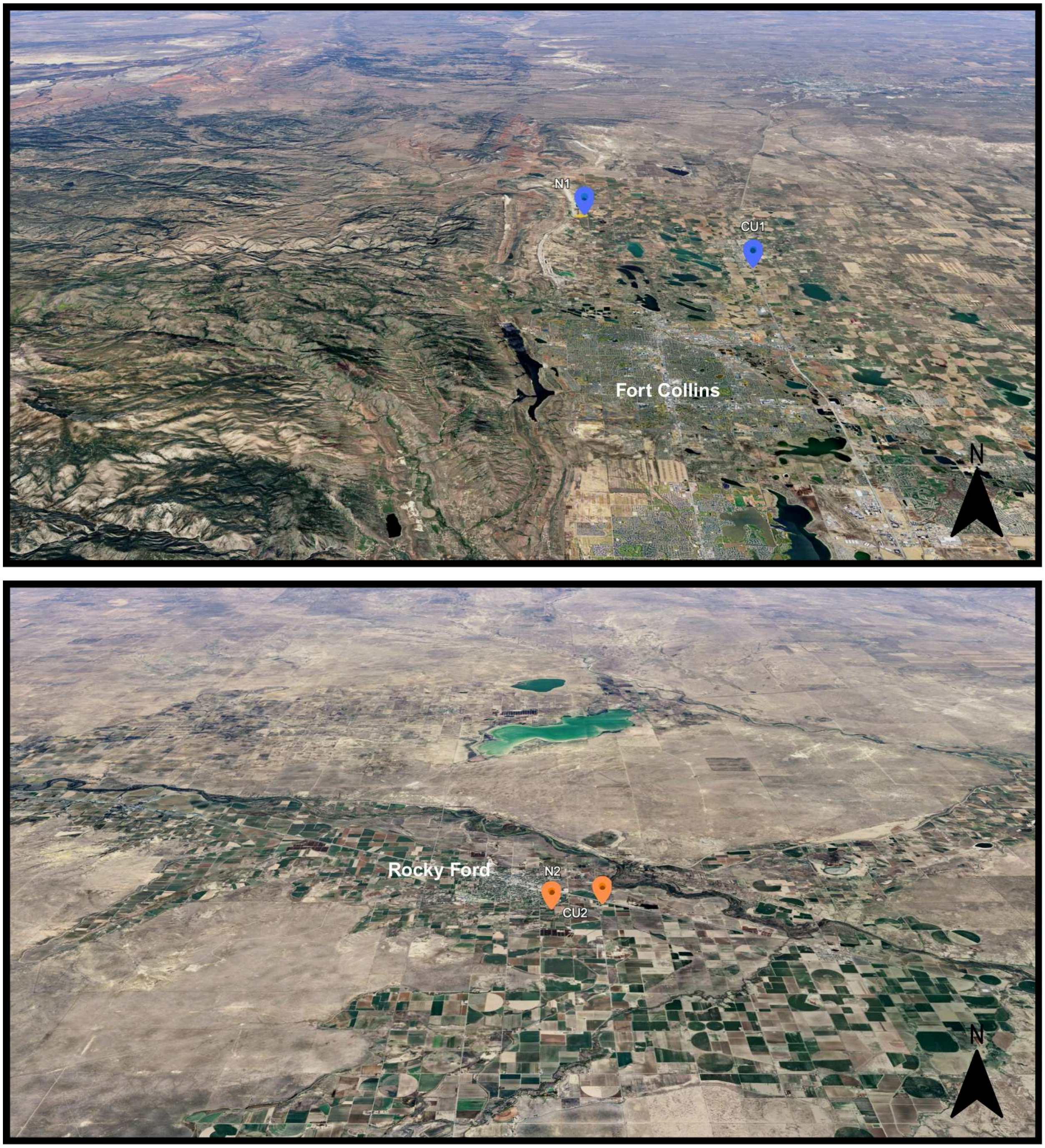
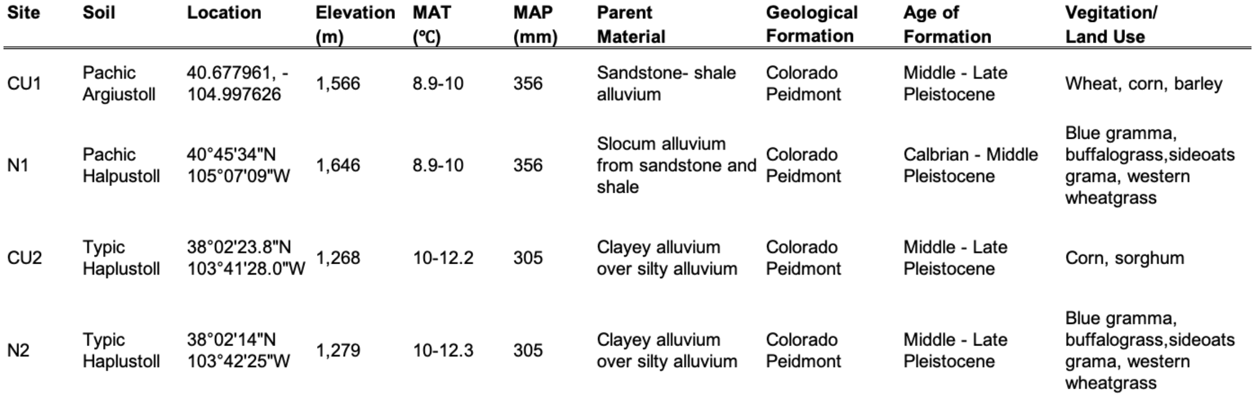


Figure 1.2. Site locations for CU1 and N1 in the South Platte watershed, as well as CU2 and N2 in the Arkansas watershed. *Image source: Google Earth, Maxar Technologies, accessed June 30, 2025.*

Table 1.1 Site descriptions for cultivated and native sites in the South Platte and Arkansas basin, CU1/N1 & CU2/N2, respectively. Geologic data were obtained from the Rockd database (Peters et al.,2018). Soil and vegetation data were obtained from the NRCS Web Soil Survey.



Site	Soil	Location	Elevation (m)	MAT (℃)	MAP (mm)	Parent Material	Geological Formation	Age of Formation	Vegitation/ Land Use
CU1	Pachic Argiustoll	40.677961, -104.997626	1,566	8.9-10	356	Sandstone- shale alluvium	Colorado Peidmont	Middle - Late Pleistocene	Wheat, corn, barley
N1	Pachic Halpustoll	40°45'34"N 105°07'09"W	1,646	8.9-10	356	Slocum alluvium from sandstone and shale	Colorado Peidmont	Calbrian - Middle Pleistocene	Blue gramma, buffalograss,sideoats grama, western wheatgrass
CU2	Typic Haplustoll	38°02'23.8"N 103°41'28.0"W	1,268	10-12.2	305	Clayey alluvium over silty alluvium	Colorado Peidmont	Middle - Late Pleistocene	Corn, sorghum
N2	Typic Haplustoll	38°02'14"N 103°42'25"W	1,279	10-12.3	305	Clayey alluvium over silty alluvium	Colorado Peidmont	Middle - Late Pleistocene	Blue gramma, buffalograss,sideoats grama, western wheatgrass

Cultivated site one (CU1) is in the South Platte Watershed Basin, within the shortgrass semiarid prairie grassland ecosystem of the Great Plains, approximately 14 km northeast of Fort Collins at the Colorado State University Agricultural Research, Development and Education Center (ARDEC) (40°67' N, -104°99' W) (Chapman et al., 2006). This site is part of the Colorado Piedmont, located in the Great Plains Province underlain by flat-lying sedimentary rock (Trimble, 1980). At an elevation of 1,566 meters, this cultivated site receives an annual precipitation of 356 mm. The average maximum temperature is 17 ℃, the average minimum temperature is 2.7 ℃, and the overall average temperature is 10 ℃. The site consists of the Garrett soil series, classified as a fine-loamy, mixed, mesic Pachic Argiustoll, developed from alluvial deposits of sandstone and shale (Kelly et al., 2008; Soil Survey Staff, 2017). The resulting soil system primarily reflects fine-textured, clay-rich soils. The crop history at this site varies annually, but has primarily been corn and wheat rotations since 2011. Soil leaching dynamics in the South Platte Basin are shaped by irrigation methods and soil properties, contributing to a high nitrate leaching risk potential.

Native site one (N1) to site 1 located in the South Platte Watershed Basin, approximately 25km northwest of Fort Collins, located on the Weaver Ranch properties (40° 45 '34"N 105° 07' 09" W). This site is part of the Colorado Piedmont, located in the Great Plains Province underlain by flat-lying sedimentary rock (Melzer & Casey 2007). At an elevation of 1,646 meters, this cultivated site receives an annual precipitation of 356 mm. The average maximum temperature is 17 ℃, the average minimum temperature is 2.7 ℃, and the overall average temperature is 10 ℃. The site consists of the Garrett soil series, classified as a fine-loamy, mixed, Pachic Haplustoll, developed from alluvium deposits of sandstone and shale (Soil Survey Staff, 2017). This land, owned by the Weaver family, has not been cultivated since the early 1900's; additionally, no records indicate that this land was cultivated under previous ownership.

Cultivated site two (CU2) is located within the Arkansas River Watershed Basin at the Rocky Ford, Colorado, at the Arkansas Valley Research Center (AVRC) (38° 02 '23.8"N 103° 41' 28.0" W). CU2 is also on the shortgrass prairie ecosystem within the Colorado Piedmont, located in the Southwestern Tablelands of the Great Plains. The AVRC agricultural plot is maintained by researchers at Colorado State University, Arkansas Valley Research Center. The MAT is 10-12.2℃, and the MAP is 305 mm (Table 1.1). The dominant soil at this site is classified as a mesic Aridic Calciustoll, developed from a Quaternary alluvium and eolian deposits of loess, silt, and sand, as well as Cretaceous shale, limestone, and sandstone. (Chapman et al. 2006; Table 1.1). The resulting soil system is characterized by coarser textures than those of the South Platte Basin. The primary crops grown at this site range annually from forage sorghum in 2024 to corn for grain in 2023. Soil leaching dynamics in this area are also shaped by irrigation methods and inherent soil properties, and the Arkansas Basin would generally be expected to have a lower nitrate leaching risk potential than the South Platte Basin.

Native site two (N2) is the corresponding native site to CU2. Arkansas River Watershed Basin 3km southwest of Rocky Ford, Colorado, at the Arkansas Valley Research Center (AVRC) (38° 02 '14"N 103° 42' 25" W). N2 is also on the shortgrass prairie ecosystem within the Colorado Piedmont, located in the Southwestern Tablelands of the Great Plains. (Figure 1.1). N2 has been used as a cemetery site since the early 1900s. The MAT is 10-12.2 ℃, and the MAP is 305 mm (Table 1.1). The dominant soil at this site is classified as a mesic Aridic Calciustoll, developed from a Quaternary alluvium and eolian deposits of loess, silt, and sand, as well as Cretaceous shale, limestone, and sandstone. (Chapman et al. 2006; Table 1.1).

2. EXPERIMENTAL DESIGN

Both CU1 and CU2 sites are pseudo-replicate research plots in different Colorado watersheds under two conservation tillage treatments, minimum (MT) and strip (ST) tillage. The conservation methods used in this study were selected by local farmers interested in testing their effectiveness on furrow-irrigated systems. Conventional tillage (CT) is designed as the control. CT involves plow-based methods that invert soil and bury residue. In contrast, ST, as a conservation practice, involves vertical and strip till operations, respectively, leaving most of the residue on the surface. All conservation tillage depths range on average from 0-3 inches, while conventional tillage depths range from 1-10 and sometimes 12 inches. The site was set up in a randomized complete block design with two blocks and three treatments per block. Field sizes are large, measuring 320 by 164 meters (5.9ha), with each of the six plots being

27 meters wide and 320 meters long, containing 36 furrows, 90cm apart, where alternate rows were irrigated (Figure 1.2).

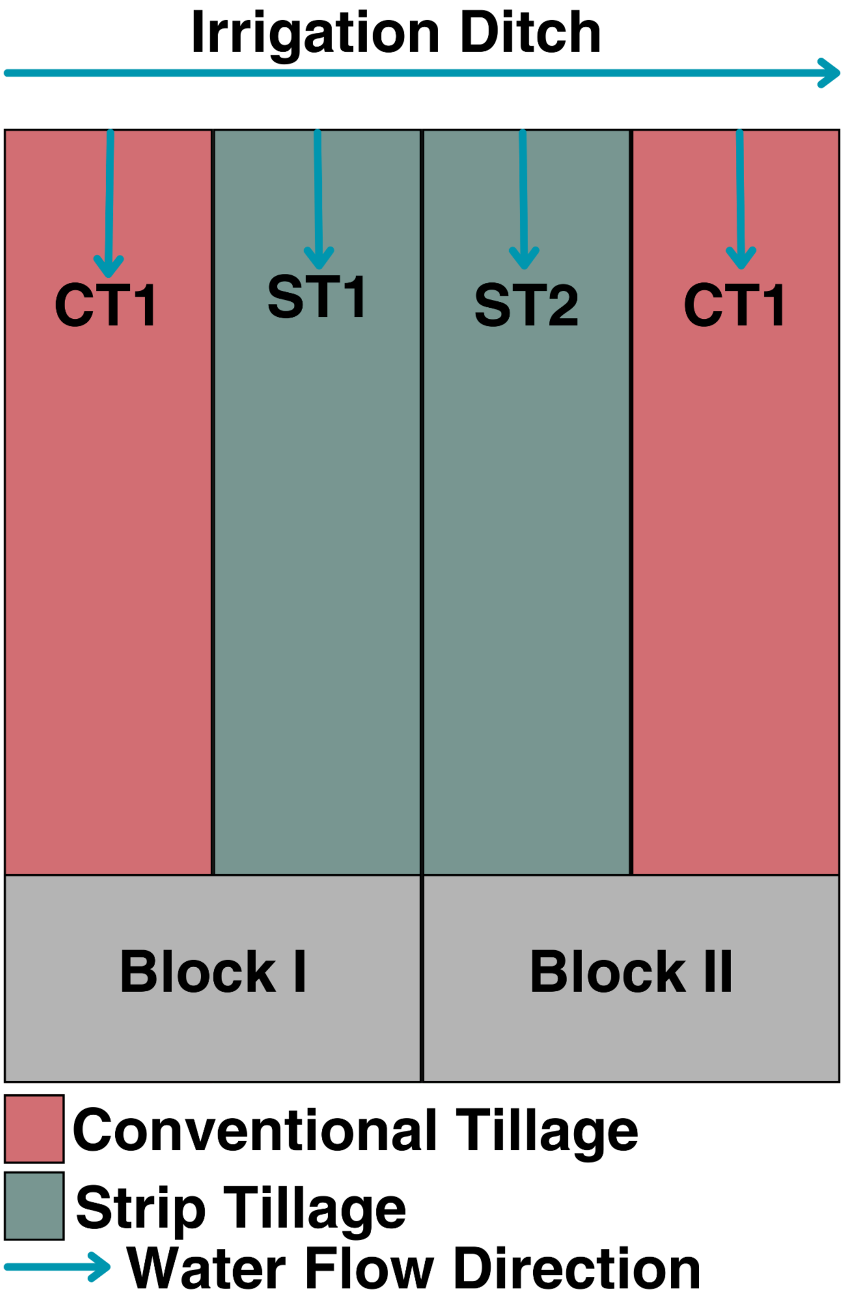


Figure 1.2. Configuration of CU1 and CU2 pseudo-replicate experimental field design. Both cultivated sites are organized in a two-block design with each block containing a conventional tillage (CT) treatment and strip tillage (ST) treatment. Each cultivated site also contains a minimal tillage treatment (MT), but it was not included in this experiment. Furrow irrigation water flows from the top of the field at each site to the bottom.

Both CU1 and CU2 sites are long-term trials to study the effects of conservation tillage on soil and water quality. This study specifically focused on comparing CT with ST only. CU1 has been following this design since 2011, whereas the AVRC (CU2) site adopted this design in 2023.

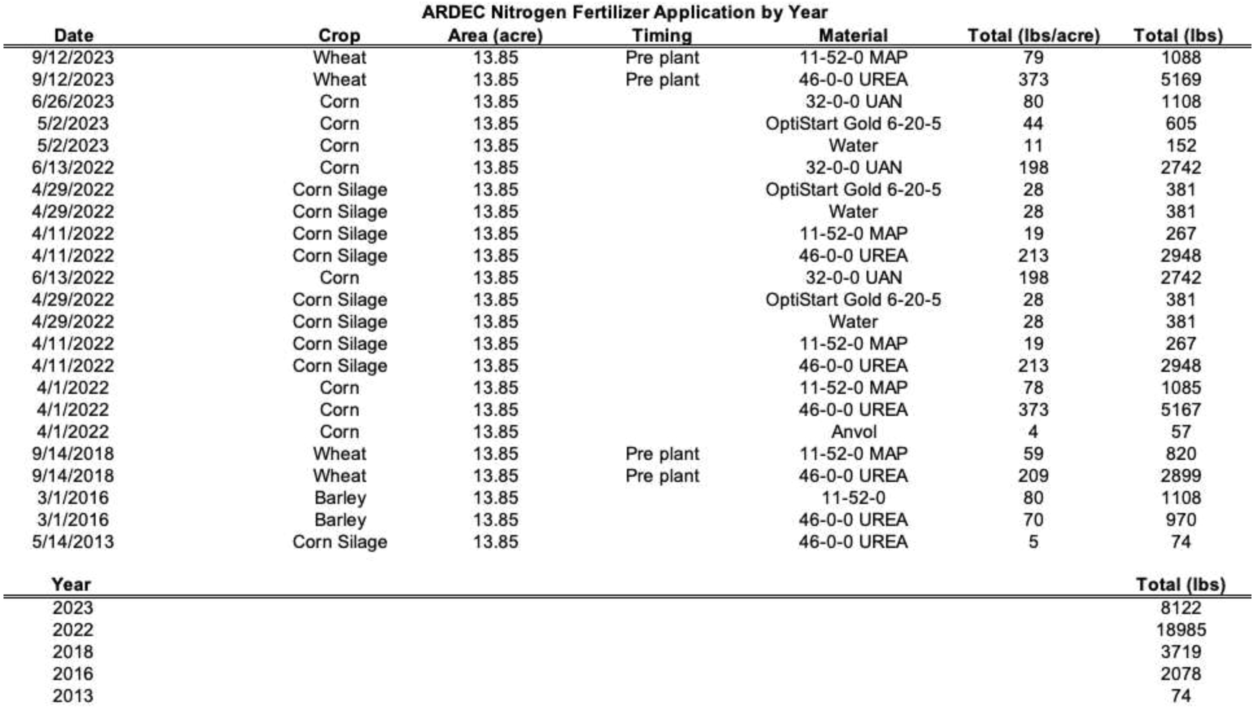
For CU1, all farming operations span six rows. Post-harvest, residues in all tillage systems were managed by chopping with a 4.6-meter-wide flail chopper, then windrowed and baled, ensuring less than 50% of the residue was removed. From 2011 to 2017, CT and ST required, on average, 9 and 6 field operations, respectively, referring to activities such as tilling, planting, spraying, and harvesting passes made across a field.

During 2011-2015, 2017, 2020-2023 at CU1, a hybrid Mycogen 2V357 corn with a 90 to 95-day maturity was planted in late April or early May. The seeds were sown at a depth of five cm with an in-row spacing of 15 cm and row spacing of 75 cm, targeting a plant population of 83,950 seeds per hectare (34,000 seeds per acre). In 2016, barley (Hordeum vulgare L.) was planted on March 3 with a seeding rate of 112 kg per hectare (100 lbs per acre). Fertility rates were determined using the Colorado State University Extension Corn Fertilizer Recommendations and pre-plant soil samples from the top 15 cm of soil. Barley was planted in 2016, beans in 2018, and winter wheat in both 2019 and 2024.

For CU1 conventional tillage plots, fertilizers were broadcast across the soil surface and then incorporated. In contrast, conservation tillage plots used side-dressing techniques for liquid fertilizer application, placing the fertilizer in subsurface bands alongside the plant rows. Details on fertilization practices are documented in Table 1.3 (FarmLogic 2025). On average, CU1 receives three irrigation events per year, each applying 2.5 inches of water, for a total of approximately 7.5 inches annually. An exception occurred in 2014 and 2015, during which the field was irrigated more intensively with five events totaling 12.5 inches (2.5 inches per event).

For CU2, all farming operations utilized implements that reflect CU1 (Table 1.4). Similar to CU1 post-harvest, residues in all tillage systems were managed by chopping, then windrowing and baling, with less than 50% of the residue removed. From 2023 to 2024, CT and ST required an average of 6 operations, respectively. All conservation tillage depths range on average from 0-3 inches, while conventional tillage depths range from 1-10 and sometimes 12 inches. In 2023, the irrigation schedule consisted of seven irrigation events over the growing season, each delivering approximately 2 inches of water per event. In 2024, the irrigation schedule consisted of six irrigation events throughout the growing season, with approximately 2 inches of water applied during each event. On average, 14 inches of irrigation is added annually at AVRC.

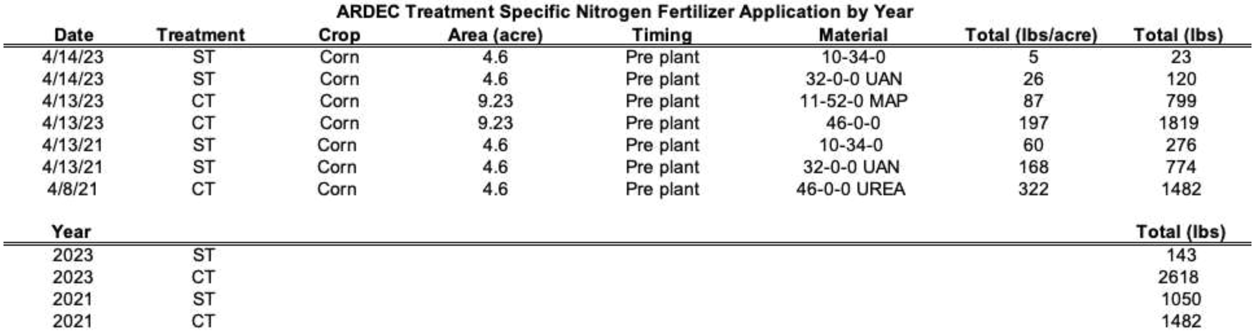
Table 1.3. The top figure illustrates nitrogen fertilizer by material type and amount by year applied to the entire field. The bottom figure illustrates additional Nitrogen applications to CT or ST treatments. Data was obtained from the software platform FarmLogic.



ARDEC Nitrogen Fertilizer Application by Year

Date	Crop	Area (acre)	Timing	Material	Total (lbs/acre)	Total (lbs)
9/12/2023	Wheat	13.85	Pre plant	11-52-0 MAP	79	1088
9/12/2023	Wheat	13.85	Pre plant	46-0-0 UREA	373	5169
6/26/2023	Corn	13.85		32-0-0 UAN	80	1108
5/2/2023	Corn	13.85		OptiStart Gold 6-20-5	44	605
5/2/2023	Corn	13.85		Water	11	152
6/13/2022	Corn	13.85		32-0-0 UAN	198	2742
4/29/2022	Corn Silage	13.85		OptiStart Gold 6-20-5	28	381
4/29/2022	Corn Silage	13.85		Water	28	381
4/11/2022	Corn Silage	13.85		11-52-0 MAP	19	267
4/11/2022	Corn Silage	13.85		46-0-0 UREA	213	2948
6/13/2022	Corn	13.85		32-0-0 UAN	198	2742
4/29/2022	Corn Silage	13.85		OptiStart Gold 6-20-5	28	381
4/29/2022	Corn Silage	13.85		Water	28	381
4/11/2022	Corn Silage	13.85		11-52-0 MAP	19	267
4/11/2022	Corn Silage	13.85		46-0-0 UREA	213	2948
4/1/2022	Corn	13.85		11-52-0 MAP	78	1085
4/1/2022	Corn	13.85		46-0-0 UREA	373	5167
4/1/2022	Corn	13.85		Anvol	4	57
9/14/2018	Wheat	13.85	Pre plant	11-52-0 MAP	59	820
9/14/2018	Wheat	13.85	Pre plant	46-0-0 UREA	209	2899
3/1/2016	Barley	13.85		11-52-0	80	1108
3/1/2016	Barley	13.85		46-0-0 UREA	70	970
5/14/2013	Corn Silage	13.85		46-0-0 UREA	5	74

Year	Total (lbs)
2023	8122
2022	18985
2018	3719
2016	2078
2013	74

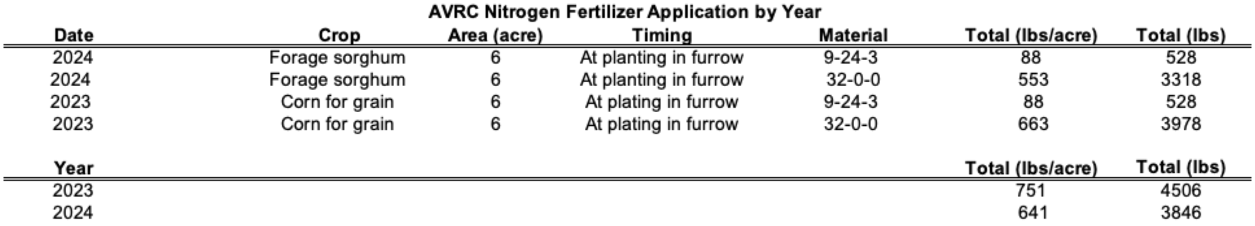


ARDEC Treatment Specific Nitrogen Fertilizer Application by Year

Date	Treatment	Crop	Area (acre)	Timing	Material	Total (lbs/acre)	Total (lbs)
4/14/23	ST	Corn	4.6	Pre plant	10-34-0	5	23
4/14/23	ST	Corn	4.6	Pre plant	32-0-0 UAN	26	120
4/13/23	CT	Corn	9.23	Pre plant	11-52-0 MAP	87	799
4/13/23	CT	Corn	9.23	Pre plant	46-0-0	197	1819
4/13/21	ST	Corn	4.6	Pre plant	10-34-0	60	276
4/13/21	ST	Corn	4.6	Pre plant	32-0-0 UAN	168	774
4/8/21	CT	Corn	4.6	Pre plant	46-0-0 UREA	322	1482

Year		Total (lbs)
2023	ST	143
2023	CT	2618
2021	ST	1050
2021	CT	1482

Table 1.4. CU2 nitrogen fertilizer by material type and amount by year applied to the whole field. Data was obtained from the software platform FarmLogic.



AVRC Nitrogen Fertilizer Application by Year

Date	Crop	Area (acre)	Timing	Material	Total (lbs/acre)	Total (lbs)
2024	Forage sorghum	6	At planting in furrow	9-24-3	88	528
2024	Forage sorghum	6	At planting in furrow	32-0-0	553	3318
2023	Corn for grain	6	At plating in furrow	9-24-3	88	528
2023	Corn for grain	6	At plating in furrow	32-0-0	663	3978

Year	Total (lbs/acre)	Total (lbs)
2023	751	4506
2024	641	3846

Tables 1.3 and 1.4 summarize nitrogen fertilizer applications at CU1 and CU2, respectively, based on records from the FarmLogic software platform. Both sites used common nitrogen sources like 9-24-3 and 32-0-0 and reported application rates and totals by year. However, CU1 had a more complex and intensive fertilization history, with a wider range of materials, application methods, and equipment types applied over a longer time span (2013–2023). It also included comparisons of conventional till (CT) and strip till (ST), with total nitrogen inputs reaching up to 18,895 lbs in 2022. In contrast, CU2 has only two years of data (2023–2024), uses fewer materials overall, uses more material per acre than CU1, applies all fertilizer in-furrow at planting, and has lower total nitrogen inputs, peaking at 4,506 lbs in 2023.

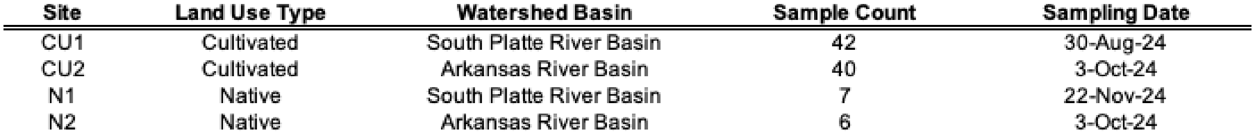
3. METHODS

3.1 FIELD METHODS

Detailed pedological studies are essential for refining nitrogen management models by providing insights into nitrogen dynamics across varied soils and landscapes. We designed our sampling scheme to closely align with the methods used by the Colorado State University Agricultural Water Quality Program (AWQP) in deep nitrate data collection at CU1 and CU2 to ensure consistency and reproducibility. This approach ensures we can accurately determine whether nitrate results are primarily influenced by soil or treatment effects (i.e., CT, ST). It is important to note that these methods were the same at both CU1 and CU2 sites.

We sampled CT and ST treatments. For the strip till treatment (ST), we sampled from the wet bed at the top and bottom of the middle row (17th) within each block. For example, in CT1/Rep 1, we sampled at the top and bottom of the middle row along the wet bed. The following scheme was reproduced for each treatment within each block. For each treatment at each location, three core samples were taken via a truck-mounted hydraulic Giddings probe machine using a 2-inch diameter by five-foot-long steel soil tube. Three representative cores were taken down to a depth of 150 cm (or to a restrictive layer) at each sampling site and compared for homogeneity. If individual cores were homogeneous in their morphological characteristics, including texture, structure, and horizon development, then horizon depth designations were made among the three, and samples were composited by horizon for each sampling location across the field. These observations provided the foundation for meaningful comparisons of soils across river basins and among their respective field sites. This approach ensured that observed differences in nitrate behavior could be interpreted within a consistent pedologic framework that reflected inherent variations in soil formation and management history. Similar sampling methods were conducted at each native site. However, we sampled at one location for each native site. Three cores were taken at each location, delineated by morphological characteristics, separated, and composited by horizon depths. A total of 95 samples were obtained and analyzed for this study (n=95) (Table 1.5).

Table 1.5. Sample count and date collected for each cultivated and native site within each watershed basin.



Site	Land Use Type	Watershed Basin	Sample Count	Sampling Date
CU1	Cultivated	South Platte River Basin	42	30-Aug-24
CU2	Cultivated	Arkansas River Basin	40	3-Oct-24
N1	Native	South Platte River Basin	7	22-Nov-24
N2	Native	Arkansas River Basin	6	3-Oct-24

$$T\ x\ B\ x\ P\ x\ Hc\ =\ Cultivated\ Site\ Sample\ Count \qquad \text{Equation 1.1}$$

For cultivated sites, T represents the number of treatments (CT, ST), B represents the number of blocks per treatment, P represents the number of sampling points per block (top and bottom), Hc and represents the average number of composited horizons per sampling point.

CU1 sample count : 2 x 2 x 2 x 5.25 = 42
CU1 sample count : 2 x 2 x 2 x 5 = 40

$$N\ x\ Hn\ =\ Native\ Site\ Sample\ Count \qquad \text{Equation 1.2}$$

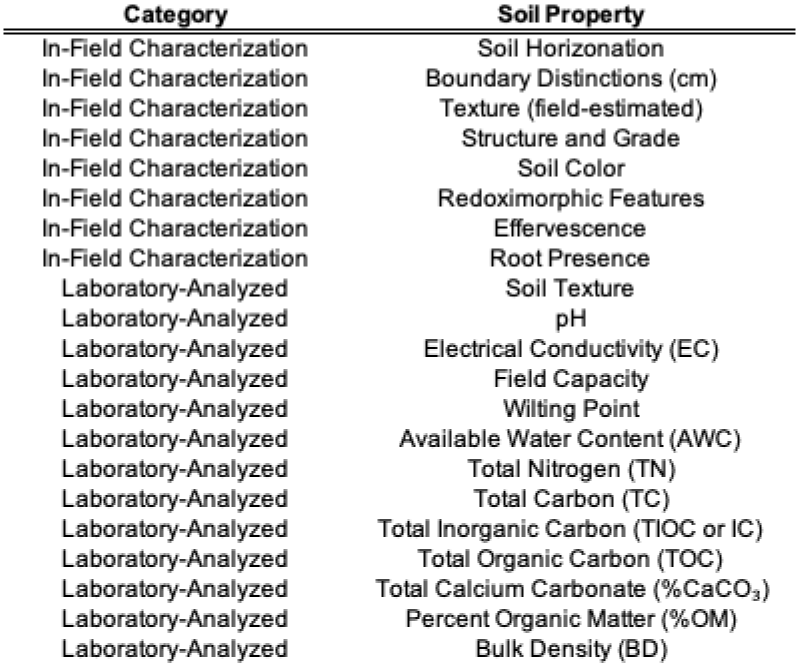
For native sites, N represents the number of native sites, Hn and represents the average number of composited horizons per native site.

Native sites sample count: 2 x 6.5 = 13

The suite of in-field soil characteristics assessed for this study includes: soil horizonation, boundary distinctions (cm), texture, structure and grade, color, presence and or absence of redoxamorphic features, effervescence, and presence or absence of roots (Table 1.6).

Samples from the pedons core samples were used for soil characterization including texture by hydrometer, pH, electrical conductivity (EC), total nitrogen, total carbon, total inorganic carbon total organic carbon, total calcium carbonate ($CaCO_3$), percent organic matter (%OM), bulk density (BD), available water capacity, wilting point, and field capacity in a laboratory setting (Table 1.6).

Table 1.6 represents the complete list of soil properties analyzed both in the field and under laboratory conditions.



Category	Soil Property
In-Field Characterization	Soil Horizonation
In-Field Characterization	Boundary Distinctions (cm)
In-Field Characterization	Texture (field-estimated)
In-Field Characterization	Structure and Grade
In-Field Characterization	Soil Color
In-Field Characterization	Redoximorphic Features
In-Field Characterization	Effervescence
In-Field Characterization	Root Presence
Laboratory-Analyzed	Soil Texture
Laboratory-Analyzed	pH
Laboratory-Analyzed	Electrical Conductivity (EC)
Laboratory-Analyzed	Field Capacity
Laboratory-Analyzed	Wilting Point
Laboratory-Analyzed	Available Water Content (AWC)
Laboratory-Analyzed	Total Nitrogen (TN)
Laboratory-Analyzed	Total Carbon (TC)
Laboratory-Analyzed	Total Inorganic Carbon (TIOC or IC)
Laboratory-Analyzed	Total Organic Carbon (TOC)
Laboratory-Analyzed	Total Calcium Carbonate (%$CaCO_3$)
Laboratory-Analyzed	Percent Organic Matter (%OM)
Laboratory-Analyzed	Bulk Density (BD)

These physical and chemical properties were selected because they collectively capture the fundamental processes governing water transport and, in turn, nitrate mobility and retention within the soil profile. Texture, structure, and bulk density determine pore size distribution, infiltration, and drainage, key controls on water and solute movement. Horizonation, color, and redoximorphic features provide morphological evidence of hydrologic conditions, identifying zones of saturation or leaching. Effervescence and calcium carbonate content reflect pedogenic development and influence soil pH and ionic interactions that can restrict infiltration or promote nitrate adsorption under certain conditions. Measurements of total carbon, total nitrogen, and percent organic matter represent biological and chemical nutrient pools that regulate nitrogen cycling through mineralization and immobilization. Available water capacity, wilting point, and field capacity quantify the soil’s ability to store and transmit water, directly linking hydrology to nutrient transport.

3.2 LABORATORY METHODS

All pedon soil samples were analyzed in a laboratory for soil texture, pH, electrical conductivity (EC), field capacity, total nitrogen (TN), total carbon (TC), total inorganic carbon (TIOC), total organic carbon (TOC), and wilting point and available water content (AWC). Bulk density (BD), percent organic matter (%OM), and percent calcium carbonate (% $CaCO_3$) were then determined by various calculations based on laboratory results.

Soil pH, EC, and AWC were determined at Colorado State University’s SPUR Campus, at the Soil, Water, and Plant Testing Laboratory in Denver, Colorado. Soil pH and EC were done by the 1:1 method (20g soil: 20 ml DI). Available water capacity was determined as the difference between the water stored at field capacity (1 bar) and at permanent wilting point (15 bar).

Particle size distribution was determined by the hydrometer method, based on Stokes’ law, using the American Society for Testing and Materials standard test method for particle-size analysis of soils (American Society for Testing and Materials, 1985).

Samples were pre - treated for the removal of calcium carbonate to enhance the separation or dispersion of aggregates in preparation for particle size analysis (PSA).

Total nitrogen (TN) and total carbon (TC) were determined via Elemental Analysis- Isotope Ratio Mass Spectrometry (EA-IRMS) at the CSU Soil Innovation Laboratory in Fort Collins, Colorado. Inorganic carbon (IC) was determined via a pressure transducer (Sherrod et al. 2002). Soil inorganic carbon was then subtracted from TC to get TOC. Percent $CaCO_3$ was then determined by equation (inorganic carbon (gramC/gramsoil *10000/12) (Sherrod et al. 2002). %OM was determined from %OC via a conversion factor of 1.9 based on the assumption that OM is 50% carbon (Pribyl, 2010). Mineral bulk density was determined by particle size analysis. Bulk density was then determined using a calculation that applied percent organic matter, estimated mineral bulk density, and the average organic matter bulk density (0.224/gm/cm^3) (Rawls, 1983).

Total quantity of soil chemical properties for all pedons in each basin (Table 1.7).

Table 1.7. Total mass-based quantities (g cm^{-3}) for carbon, nitrogen, $CaCO_3$, inorganic and organic carbon, clay, organic matter, and average nitrate across all pedons grouped by site, treatment, and field location.

Pedon Quantity Totals

Site	Treatment	Field Location	Total C (g/cm^3)	Total N (g/cm^3)	$CaCO_3$ (g/cm^3)	Inorganic C (g/cm^3)	Organic C (g/cm^3)	Clay (g/cm^3)	Organic Matter (g/cm^3)	Avg. Nitrate (g/cm^3)
CU1	CT1	N	244.5042	11.188341	1,441.1985	172.94382	71.56033	8,217.529	135.9646	665.5777
CU1	CT1	S	244.4473	16.573593	1,006.0813	120.72975	123.71757	7,167.479	235.0634	713.5782
CU1	CT2	N	257.5397	16.658663	1,035.1533	124.21839	133.32135	6,860.677	253.3106	558.2287
CU1	CT2	S	277.2565	19.474387	1,023.4604	122.81525	154.44127	7,924.134	293.4384	792.0413
CU1	ST1	N	214.3633	16.135338	924.7311	110.96774	103.39553	6,919.170	196.4515	491.0112
CU1	ST1	S	251.3878	19.955198	871.3118	104.55742	146.83043	9,149.776	278.9778	630.8379
CU1	ST2	N	272.1911	17.476635	1,244.8042	149.37650	122.81456	7,718.933	233.3477	553.1613
CU1	ST2	S	269.9385	18.378086	1,043.4937	125.21925	144.71928	8,079.515	274.9666	612.7523
CU2	CT1	N	218.7822	10.318957	1,206.4618	144.77542	74.00675	6,456.153	140.6128	281.8613
CU2	CT1	S	224.3917	9.088870	1,365.8035	163.89642	60.49524	5,971.151	114.9409	2,010.2595
CU2	CT2	N	226.2895	9.564550	1,397.5693	167.70832	58.58122	5,831.877	111.3043	335.8197
CU2	CT2	S	271.2591	13.440727	1,297.5052	155.70062	115.55848	6,528.702	219.5611	350.5217
CU2	ST1	N	249.5438	11.714177	1,296.5980	155.59176	93.95199	5,735.306	178.5088	775.0848
CU2	ST1	S	193.0262	10.015671	1,119.4751	134.33701	58.68920	6,152.425	111.5095	524.9948
CU2	ST2	N	206.7419	9.895189	1,274.4983	152.93979	53.80208	6,037.334	102.2239	401.4117
CU2	ST2	S	243.7825	10.928519	1,394.3172	167.31806	76.46443	6,621.916	145.2824	593.8422
N1	-	-	482.9980	17.278317	0.0000	11.24683	471.75113	5,847.713	896.3271	0.0000
N2	-	-	453.8287	10.490928	0.0000	11.18728	442.64139	5,729.134	841.0186	0.0000

Total quantity for each soil property displayed in Table 1.7 was calculated on a volume-weight basis by multiplying the percent of that given property for each horizon by bulk density and horizon thickness, and summing the total quantity to a depth of 150cm.

CHAPTER 2: PEDOLOGIC PROPERTIES RESULTS AND DISCUSSION

1. INTRODUCTION

Soil contains layers (horizons) of varying amounts of weathered minerals, organic matter, living organisms, gases, and water. As parent material undergoes weathering, it experiences both chemical and physical transformations. Additionally, within the soil profile, minerals are translocated (moved through various processes). Contributing to the soil's dynamic nature, additions and losses of organic and inorganic material influence its development or degradation over time. Agricultural soils often receive regular inputs of nitrogen and other fertilizers during a growing season. When exposed to irrigation or precipitation, these chemical inputs can be lost through leaching. Because nitrate, a common form of nitrogen, is highly soluble, it moves easily through the soil profile with water. Depending on vadose-zone conditions and nitrogen and irrigation management practices, the time delay between nitrate leaching from the root zone and its entry into groundwater can range from a few weeks to 30 years (Frank et al., 1991).

Soil properties play a critical role in governing fluid movement through the soil profile, ultimately influencing the fate and transport of nitrate. The identification of key pedogenic properties that drive nitrate fate and transport has become critical in soil science, especially amid growing concerns about nitrate leaching, greenhouse gas emissions, and agricultural productivity. A substantial body of research has sought to identify the key soil properties that drive nitrate movement; however, the specific factors influencing nitrate concentration and leaching potential within, and particularly below, the root zone remain understudied in conservation tillage systems within Colorado's agricultural soils.

Soil texture is strongly tied to the grain-size characteristics of the parent material (Kelly 1984). Textural characteristics influence the rate and depth of leaching in the soil profile, and the degree of leaching influences many other soil properties (Aguilar 1984). Particle size distribution determines pore size and connectivity in the soil matrix, directly influencing the rate and pattern of water infiltration and nitrate leaching. Soil pH governs microbial activity and nitrogen transformations, shaping nitrate persistence and potential loss pathways. Electrical conductivity reflects the total ionic strength of the soil solution and can indicate nutrient loading and leaching risk. Field capacity and wilting point define the upper and lower limits of soil water retention, with available water content (AWC) capturing the volume of water, and therefore, nitrate available for plant uptake and downward transport. Total nitrogen content represents the overall nitrogen reservoir, while total carbon and total organic carbon contribute to soil aggregation and water retention, indirectly affecting solute mobility. Inorganic carbon and calcium carbonate influence pH buffering and interact with nitrate through mineral associations. Percent organic matter improves porosity and water-holding capacity, thereby modulating nitrate retention or loss. Bulk density and mineral bulk density affect soil compaction and pore volume, which are critical determinants of water movement. Horizonation and boundary distinctions within the profile help define pathways and barriers to fluid movement. Field-estimated texture, structure, and grade influence hydraulic behavior and preferential flow paths. Soil color often correlates with moisture and organic content, while redoximorphic features indicate fluctuating water tables and potential denitrification zones. Effervescence serves as a proxy for carbonate presence, which may affect nitrate solubility and retention. Lastly, root presence enhances macroporosity and the formation of biological channels for the movement of water and nitrate. Collectively, these properties are expected to strongly influence the soil's capacity to transport, retain, or transform nitrate and are essential for understanding the vulnerability of agricultural soils to nitrate leaching.

2. SECTION OBJECTIVES AND METHODOLOGY

2.1 SECTION OBJECTIVES

This chapter aims to identify the key soil properties that behave as regulators of nitrate movement within cultivated soils in Colorado. To achieve this objective, pedon chemical and morphological characteristics were obtained, and statistical approaches were utilized to determine the key indicators of nitrate movement.

3. RESULTS

3.1 SOIL CLASSIFICATION

The pedological soil characterization at each site indicates the extent to which the hydropedology contributes to highly water-soluble nitrate movement. ARDEC (CU1) and native site (N1) in the South Platte watershed basin are Pachic Argiustolls (Garrett Series), a typical soil of Colorado grassland ecosystems, Mollisols with an argillic horizon in a ustic soil moisture regime (dry 90-180 days/year). AVRC (CU2) and native site (N2) in the Arkansas River watershed basin are Typic Halpustolls, which are also Mollisols with an ustic soil moisture regime. Both soil orders indicate that the soils are well developed by pedogenic processes, with dark, organic-matter-rich surface horizons.

3.2 SOIL MORPHOLOGY

The horizon differentiation, texture, structure, color, and other features at both regions indicate long-term soil development (Table 2.1 and 2.2).

Table 2.1. Pedon descriptions for CU1 and corresponding native site N1 represent the soil morphological characteristics at each site.

Site	Treatment	Field Loc	Furrow Type	Horizon	Depth (cm)	Class	Color Moist	Grade	Type	Redox Conc	Redox Depl	Eff.	Roots (cm)
CU1	CT1	N	Wet	Ap	0-10	SCL	10YR 3/3	2	SBK	N	N	SL	Y
CU1	CT1	N	Wet	Btk1	10-47	CL	10YR 3/4	2	SBK	N	N	ST	Y
CU1	CT1	N	Wet	Btk2	47-70	C	10YR 3/3	2	SBK	N	N	ST	Y
CU1	CT1	N	Wet	Btk3	70-95	C	10YR 5/4	2	SBK	N	N	ST	Y
CU1	CT1	N	Wet	BC	95-150+	CL	5YR 4/3	2	M	N	N	ST	Few
CU1	CT1	S	Wet	Ap	0-20	CL	10YR 3/2	1	SBK	N	N	SL	Y
CU1	CT1	S	Wet	Bt1	20-42	CL	7.5YR 3/3	1-2	PR/SBK	N	N	SL	Y
CU1	CT1	S	Wet	Btk1	42-60	C	7.5YR3/3	2	SBK	N	N	SL	Y
CU1	CT1	S	Wet	Btk2	60-71	C	5YR 3/3	2	SBK	N	N	SL	Y
CU1	CT1	S	Wet	Btk3	71-85	SCL	7.5YR 3/3	2	SBK	N	N	SL/ST	Y
CU1	CT1	S	Wet	BCk	85-110	SCL	10YR 4/3	1	M	N	N	ST	Y
CU1	CT2	N	Wet	Ap	0-15	SC	10YR 3/3	2	SBK	N	N	SL	Y
CU1	CT2	N	Wet	Btk1	15-33	C	7.5YR 3/3	2	SBK	N	N	SL	Y
CU1	CT2	N	Wet	Btk2	33-52	C	5YR 4/4	2	SBK	N	N	SL	Y
CU1	CT2	N	Wet	Bt1	52-75	C	10YR 3/3	2	SBK	N	N	SL	Y
CU1	CT2	N	Wet	Bt2	75-102	SCL	10YR 4/3	2	SBK	N	N	SL	Y
CU1	CT2	N	Wet	BC	102+	SL	10YR 4/4	2	M	N	N	ST	Y
CU1	CT2	S	Wet	Ap	0-15	CL	10YR 3/2	2	SBK	N	N	SL	Y
CU1	CT2	S	Wet	Bt1	15-43	CL-	7.5YR 3/3	2	SBK	N	N	SL	Y
CU1	CT2	S	Wet	Bt2	43-76	C	7.5YR 3/3	2	SBK	N	N	SL	Y
CU1	CT2	S	Wet	Btk	76-114	C	5YR 3/3	2	SBK	N	N	ST	Y
CU1	CT2	S	Wet	BC	114+	CL	7.5YR 4/4	2	M	N	N	ST/VE	Y
CU1	ST1	N	Wet	Ap	0-22	CL	10YR 3/3	2	ABK	N	N	SL	Y
CU1	ST1	N	Wet	Btk	22-44	SCL	5YR 3/3	2	SBK	N	N	SL	Y
CU1	ST1	N	Wet	Bt1	44-78	SCL	7.5YR 4/3	2	SBK	N	N	SL	Y
CU1	ST1	N	Wet	Bt2	78-116	SCL	10YR 4/3	2	SBK	N	N	SL	Y
CU1	ST1	N	Wet	BC	116-150+	SCL	10YR 4/4	1-2	M	N	N	ST	Few
CU1	ST1	S	Wet	Ap	0-15	CL	10YR 3/2	2	SBK	N	N	SL	Y
CU1	ST1	S	Wet	Bt1	15-45	CL-	7.5YR 3/4	2	SBK	N	N	SL	Y
CU1	ST1	S	Wet	Btk	45-75	C	5YR 3/2	2	ABK	N	N	SL	Y
CU1	ST1	S	Wet	Bt2	75-102	C	7.5YR 3/3	2	SBK	N	N	SL	Y
CU1	ST1	S	Wet	BC	102-150+	C	5YR 4/3	2	M	N	N	ST	Few
CU1	ST2	N	Wet	Ap	0-10	SCL	10YR 3/3	2	SBK	N	N	SL	Y
CU1	ST2	N	Wet	Btk1	10-31	CL	10YR 3/4	2	ABK	N	N	SL	Y
CU1	ST2	N	Wet	Btk2	31-57	C	7.5YR 3/3	2	SBK	N	N	SL	Y
CU1	ST2	N	Wet	Bt	57-100	SCL	7.5YR 3/2	2	SBK	N	N	SL	Y
CU1	ST2	N	Wet	BCk	100+	SC	5YR 3/3	2	M	N	N	ST	Y
CU1	ST2	S	Wet	Ap	0-15	CL	10YR 3/3	2	SBK	N	N	VS	Y
CU1	ST2	S	Wet	Bt1	15-45	CL	7.5YR 3/3	2	ABK	N	N	VS	Y
CU1	ST2	S	Wet	Bt2	45-60	C	5YR 4/4	2	SBK	N	N	VS	Y
CU1	ST2	S	Wet	Btk1	60-94	SiC	10YR 3/4	2	SBK	N	N	SL	Y
CU1	ST2	S	Wet	BCk	94-119	SiC	10YR 5/4	2	SBK	N	N	ST	Few
N1	-	-	-	A	0-9	CL	10YR 3/3	2	GR	N	N	SL	Y
N1	-	-	-	BA	9-26	CL	10YR 3/4	2	SBK	N	N	SL	Y
N1	-	-	-	Bt1	26-51	SiCL	7.5YR 3/3	2	SBK	N	N	SL	Y
N1	-	-	-	Bt2	51-75	SiCL	7.5 YR 3/3	2	SBK	N	N	SL	Y
N1	-	-	-	Bt3	75-95	C	5YR 4/4	2	SBK	N	N	SL	Y
N1	-	-	-	BCk	95-106	CL	10YR 3/4	2	SBK	N	N	ST	Y
N1	-	-	-	Ck	106+	SCL	10YR 3/3	2	SBK	N	N	VE	Few

Table 2.2. Pedon descriptions for CU2 and corresponding native site N2 represent the soil morphological characteristics at each site.

Site	Treatment	Field Loc	Furrow Type	Horizon	Depth (cm)	Class	Color Moist	Grade	Type	Redox Conc	Redox Depl	Eff.	Roots (cm)	Notes
CU2	CT1	N	Wet	Ap1	0-29	C	10YR 3/2	2-3	GR	N	N	SL	Y	
CU2	CT1	N	Wet	Ap2	29-52	CL	10YR 3/3	2	SBK	N	N	SL	Y	
CU2	CT1	N	Wet	Bk1	52-93	CL	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	CT1	N	Wet	Bk2	93-127	CL	10YR 4/3	1-2	SBK	N	N	ST	Y	
CU2	CT1	N	Wet	Bk3	127+	SiL	10YR 4/4	1	SBK	N	N	ST/VE	Few	
CU2	CT1	S	Wet	Ap1	0-28	CL	10YR 3/2	3	GR	N	N	SL	Y	
CU2	CT1	S	Wet	Ap2	28-47	CL	10YR 3/3	2	SBK	N	N	ST	Y	
CU2	CT1	S	Wet	Bk1	47-89	L	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	CT1	S	Wet	Bk2	89-135	L	10YR 4/3	2	SBK	N	N	ST	Y	
CU2	CT1	S	Wet	Bk3	135+	CL	10YR 4/4	1	SBK	N	N	VE	Few	
CU2	CT2	N	Wet	Ap1	0-31	CL	10YR 3/2	2	GR	N	N	SL	Y	
CU2	CT2	N	Wet	Ap2	31-44	CL	10YR 3/3	2	SBK	N	N	ST	Y	
CU2	CT2	N	Wet	Bk1	44-81	SCL	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	CT2	N	Wet	Bk2	81-120	L	10YR 4/3	2	SBK	N	N	ST	Y	
CU2	CT2	N	Wet	Bk3	120+	L	10YR 4/4	1	SBK	N	N	SL/ST	Y	
CU2	CT2	S	Wet	Ap1	0-23	C	10YR 3/2	2-3	GR	N	N	VS	Y	
CU2	CT2	S	Wet	Ap2	23-47	C	10YR 3/3	2	SBK	N	N	ST	Y	
CU2	CT2	S	Wet	Bk1	47-90	SCL	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	CT2	S	Wet	Bk2	90-127	SCL	10YR 4/3	2	SBK	N	N	ST	Y	
CU2	CT2	S	Wet	Bk3	127+	L	10YR 4/4	1-2	M	N	N	ST	Very Few	
CU2	ST1	N	Wet	Ap1	0-30	C	10YR 3/2	3	GR	N	N	SL	Y	
CU2	ST1	N	Wet	Ap2	30-61	CL	10YR 3/3	2	SBK	N	N	ST	Y	
CU2	ST1	N	Wet	Bk1	61-93	L	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	ST1	N	Wet	Bk2	93-125	L	10YR 4/3	2	SBK	N	N	ST	Y	
CU2	ST1	N	Wet	Bk3	125+	SiCL	10YR 4/4	1-2	M	N	N	ST	Very Few	
CU2	ST1	S	Wet	Ap1	0-35	C	10YR 3/2	3	GR	N	N	VS	Y	
CU2	ST1	S	Wet	Ap2	35-51	CL	10YR 3/3	2	SBK	N	N	SL	Y	
CU2	ST1	S	Wet	Bk1	51-90	L	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	ST1	S	Wet	Bk2	90-128	L	10YR 4/3	2	SBK	N	N	ST	Y	
CU2	ST1	S	Wet	Bk3	128+	CL	10YR 4/4	1-2	M	N	N	ST	Very Few	
CU2	ST2	N	Wet	Ap1	0-30	CL	10YR 3/2	3	GR	N	N	SL	Y	
CU2	ST2	N	Wet	Ap2	30-57	CL	10YR 3/3	2	SBK	N	N	ST	Y	
CU2	ST2	N	Wet	Bk1	57-91	L	10YR 5/3	2	SBK	N	N	VE	Y	
CU2	ST2	N	Wet	Bk2	91-127	L	10YR 4/3	2	SBK	N	N	VE	Y	
CU2	ST2	N	Wet	Bk3	127+	SiCL	10YR 4/4	1	M	N	N	ST	Few	
CU2	ST2	S	Wet	Ap1	0-36	C	10YR 3/2	3	GR	N	N	VS	Y	
CU2	ST2	S	Wet	Ap2	36-53	SCL	10YR 3/3	2	SBK	N	N	SL	Y	
CU2	ST2	S	Wet	Bk1	53-92	L	10YR 5/3	2	SBK	N	N	ST	Y	
CU2	ST2	S	Wet	Bk2	92-130	CL	10YR 4/3	2	SBK	N	N	ST	Y	
CU2	ST2	S	Wet	Bk3	130+	L	10YR 4/4	1	M	N	N	ST	Few	
N2	-	-	-	A	0-13	C	10YR 3/2	2	GR	N	N	VS	Y	
N2	-	-	-	A	13-34	C	10YR 3/3	2	SBK	N	N	VS	Y	
N2	-	-	-	Btk1	34-64	CL	10YR 5/3	2	SBK	N	N	SL	Y	
N2	-	-	-	Bk1	64-85	CL	10YR 4/3	2	SBK	N	N	SL	Y	
N2	-	-	-	Bk2	85-120	L	10YR 4/4	2	SBK	N	N	SL	Y	
N2	-	-	-	Bk3	120+	SCL	10YR 3/4	2	SBK	N	N	SL	Y	

ARDEC

Clay Distribution

At CU1, clay content exhibited distinct vertical patterns across treatments and locations, as shown in Figure 2.1. Shale and sandstone alluvium parent material results in a fine soil texture and a high clay-content distribution throughout the profile. Across all treatments and field locations, clay distribution generally increases vertically with depth, with maximum total amount typically occurring in the last 50cm of the profile, ranging from 1,500-3000g/cm^2. The average clay content at CU1 is 1477 g/cm^3 to a depth of 150cm. Sharp increases in clay at CU1 typically occur between 50 and 100cm, consistent with an argillic horizon. Treatment level differences were not observed. The total average clay quantity was noticeably lower at N1, averaging 835 g/cm^3.

Bulk Density

At CU1, all pedons exhibited noticeable trends in bulk density (BD). CU1 and CU2 resulted in similar BD at equivalent depths. The mean BD at CU1 and N1 was 1.37g/cm^3 and 1.07g/cm^3, respectively. In CU1, bulk density generally increased across most treatments and locations within the 25–75 cm depth range (Figure 2.7). In contrast, N1 started with the lowest surface BD compared to CU1 and CU2 and gradually increased with depth, remaining lower than cultivated sites at comparable depths.

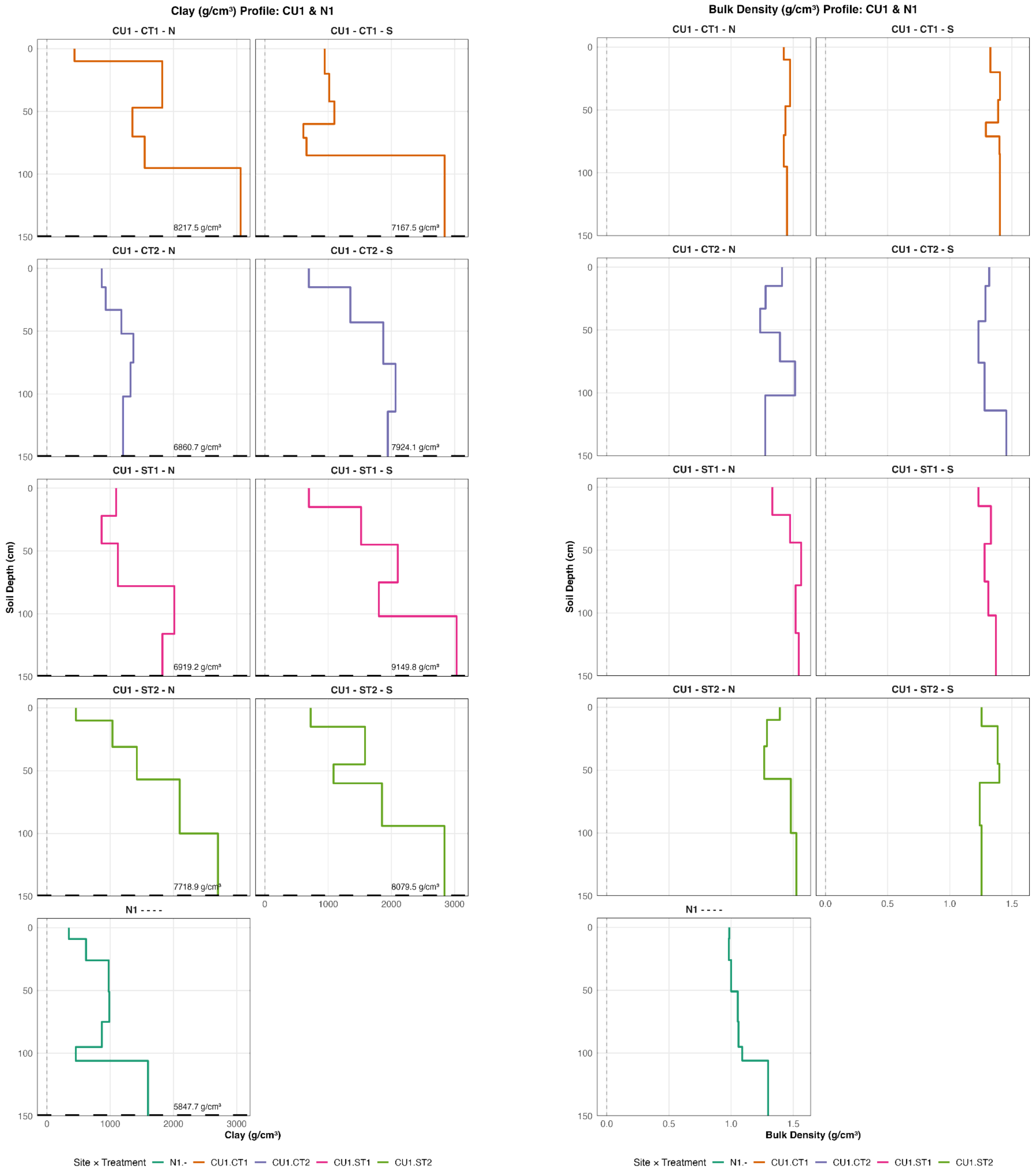


Figure 2.1. A (left) Total clay as a function of soil depth for CU1 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N1 the corresponding native site is included. B (right) Bulk density as a function of depth for similar treatments, field locations, and native site N2.

AVRC

Clay Distribution

Coarse soil textures and weaker clay content distribution at CU2, resulting from the coarser-grained alluvial parent material as compared to CU1 (South Platte Basin), are demonstrated in the depth profile in Figure 2.2 A. Generally, across treatments and locations, clay distribution near the surface is highest between 0-40cm, followed by a sharp decrease between 40-50cm. Clay content then generally increases throughout the rest of the profile to equivalent amounts near the surface. The total average quantity of clay at CU2 is 1233 g/cm^3. Treatment level differences were not observed. The total average clay quantity was noticeably lower at N2, averaging 954 g/cm^3.

Bulk Density

The mean BD at CU2 and N2 was 1.41g/cm^3 and 1.19g/cm^3 respectively. CU2 consistently exhibited a sharp increase in BD between 25–125 cm (Figure 2.2 B). N2 started with the lowest surface BD compared to CU1 and CU2 and gradually increased with depth, remaining lower than cultivated sites at comparable depths.

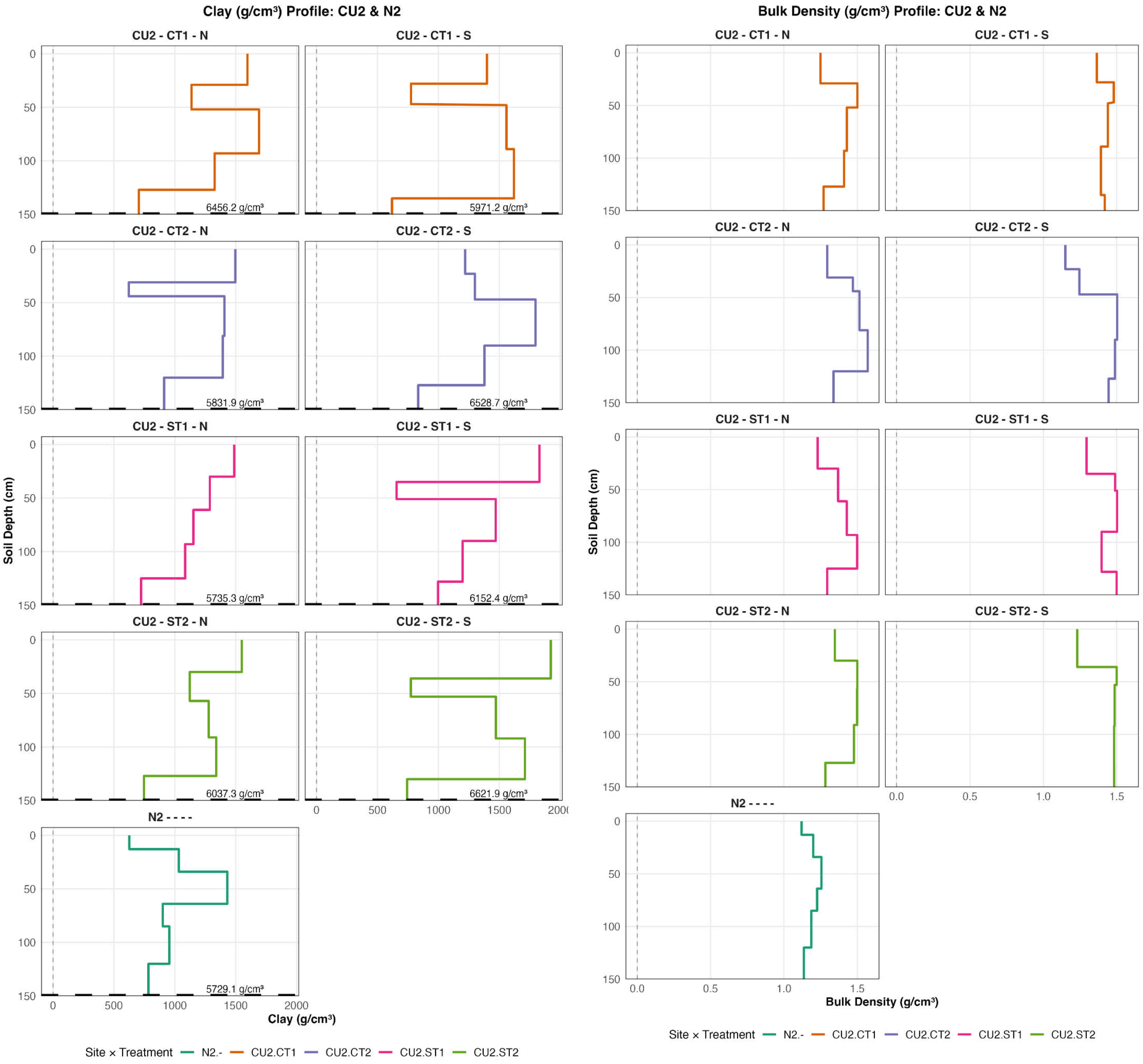


Figure 2.2. A(left) Percent clay as a function of soil depth for CU2 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N2 the corresponding native site is included. B (right) Bulk density as a function of depth for similar treatments, field locations, and native site N2.

The vertical clay distribution also exhibited distinct patterns across cultivated systems and geographically different watershed basins, as shown in Figure 2.3.

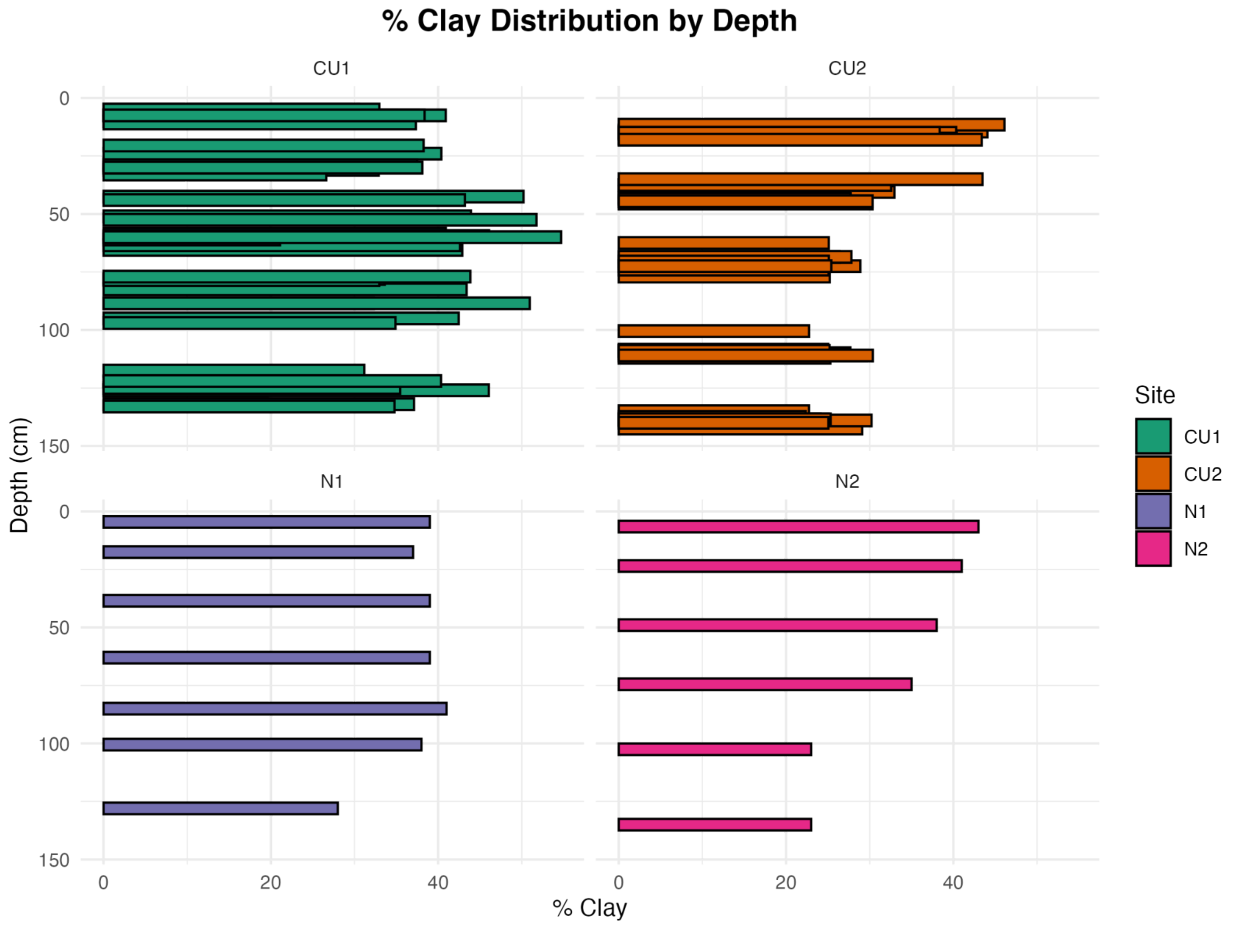


Figure 2.3. % Clay content as a function of soil depth for CU1, CU2, N1, and N2.

The dominant soil texture classes varied notably across site and treatment combinations, revealing both vertical and spatial heterogeneity. At CU1, finer textures such as clay loam (CL) and sandy clay (SC) were more prevalent, particularly in deeper horizons. CL was predominant in the surface layers, and clay (C) in the middle horizons bands.

CU2 exhibited a high proportion of clay texture in the surface horizons across all treatments, transitioning to loams (L), sandy clay loams (SCL), and CL with depth. The ST treatments in both CU1 and CU2 tended to have more stratified horizons, suggesting potential effects of surface management. In contrast, the N1 and N2 profiles displayed greater heterogeneity with less predictable vertical transitions, indicating a more complex depositional or disturbance history. These patterns underscore the influence of both site conditions and treatment practices on the vertical distribution of soil texture.

CU1 and N1 color transitions in Hue from brown to (10YR & 7.5YR 3/3) in the upper horizons, indicating a significant percentage of organic matter, to reddish brown (5YR 3/3) near the lower horizons. CU2 and N2 have similar coloration throughout the soil profile (10YR), transitioning from 10YR 5/2 in surface horizons to 10YR 6/3 in lower horizons (Table 2.2).

Soil structure varied across sites, treatments, and depth intervals as shown in Figure 2.4.

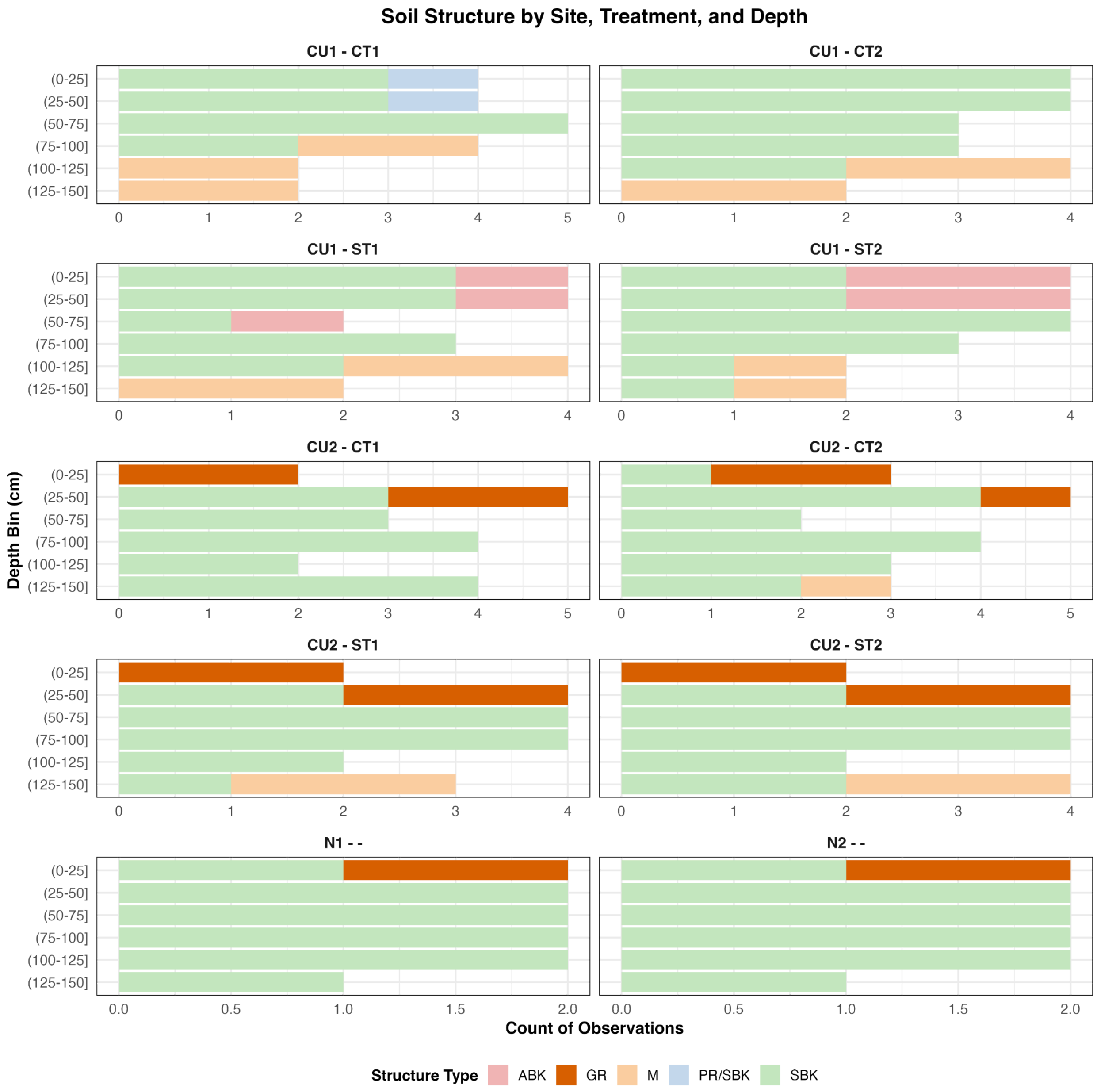


Figure 2.4. Dominant soil structure as a function of soil depth for CU1, CU2, N1, and N2.

Subangular blocky (SBK) structure was dominant across nearly all sites and depth bins, especially below 50 cm, indicating consistent aggregation in subsurface horizons. Granular (GR) and angular blocky (ABK) structures were more frequent in surface horizons (0–50 cm), particularly in the CU1-ST1 and CU1-ST2 treatments. Massive (M) structure occurred sporadically in deeper layers, notably in CU2-ST2 and CU1-ST2. Native undisturbed sites (N1 and N2) showed a more uniform SBK dominance with minor GR structure, highlighting natural pedogenic stability.

3.3 SOIL CHEMICAL PROPERTIES

The soil chemical properties observed in both regions also indicate long-term soil development (Tables 2.3 and 2.4).

Table 2.3. Soil Chemical properties for site CU1 and N1 in the South Platte Basin.

Site	Treatment	Field Loc	Furrow Type	Horizon	Depth (cm)	pH	EC	TC	TN	C:N	Total $CaCO_3$	TOIC	TOC	OM %	ρb	Sand %	Clay %	Silt %	Field Cap	Wilt Point	AWC
CU1	CT1	N	Wet	Ap	0-10	8.2	0.67	1.30	0.10	13.65	3.80	0.46	0.84	1.60	1.42	46.56	30.54	22.90	34.11	15.11	19.00
CU1	CT1	N	Wet	Btk1	10-47	8.1	0.68	0.86	0.06	14.27	3.86	0.46	0.40	0.76	1.47	42.13	33.44	24.43	20.28	15.46	4.82
CU1	CT1	N	Wet	Btk2	47-70	8.2	0.87	0.74	0.06	13.03	3.27	0.39	0.35	0.66	1.44	37.35	40.92	21.74	23.55	19.75	3.79
CU1	CT1	N	Wet	Btk3	70-95	8.4	0.57	1.56	0.05	33.08	10.46	1.26	0.30	0.58	1.42	33.62	43.40	22.98	25.72	17.81	7.91
CU1	CT1	N	Wet	BC	95-150+	8.2	1	1.24	0.04	33.18	8.72	1.05	0.19	0.37	1.45	34.73	38.39	26.87	20.67	16.01	4.66
CU1	CT1	S	Wet	Ap	0-20	8.4	0.24	1.51	0.13	11.54	4.07	0.49	1.02	1.94	1.33	32.61	35.60	31.79			
CU1	CT1	S	Wet	Bt1	20-42	8.2	0.36	1.20	0.09	13.80	4.75	0.57	0.63	1.20	1.40	38.01	32.89	29.10			
CU1	CT1	S	Wet	Btk1	42-60	8.4	0.24	0.82	0.07	10.97	2.75	0.33	0.49	0.93	1.39	31.53	43.92	24.54			
CU1	CT1	S	Wet	Btk2	60-71	8.2	0.48	2.34	0.13	18.32	11.81	1.42	0.92	1.76	1.29	25.59	42.88	31.53			
CU1	CT1	S	Wet	Btk3	71-85	8.3	0.48	1.97	0.13	14.67	7.49	0.90	1.07	2.03	1.40	45.71	33.61	20.68			
CU1	CT1	S	Wet	BCk	85-110	8.2	0.55	2.14	0.12	18.29	10.50	1.26	0.88	1.66	1.40	45.45	31.17	23.38			
CU1	CT2	N	Wet	Ap	0-15	8.4	0.22	1.78	0.12	14.62	6.15	0.74	1.04	1.98	1.41	45.03	40.91	14.06			
CU1	CT2	N	Wet	Btk1	15-33	8.3	0.3	2.07	0.13	16.01	8.68	1.04	1.03	1.96	1.28	26.82	40.38	32.81			
CU1	CT2	N	Wet	Btk2	33-52	8.6	0.22	2.36	0.10	23.70	6.76	0.81	1.55	2.94	1.23	13.40	50.20	36.40			
CU1	CT2	N	Wet	Bt1	52-75	8.3	0.3	0.99	0.08	12.80	3.89	0.47	0.52	0.99	1.39	33.58	42.61	23.81			
CU1	CT2	N	Wet	Bt2	75-102	8.4	0.22	0.70	0.06	11.13	2.69	0.32	0.37	0.71	1.51	50.28	32.32	17.40			
CU1	CT2	N	Wet	BC	102+	8.3	0.28	0.89	0.06	15.17	4.90	0.59	0.30	0.57	1.27	69.82	19.65	10.53			
CU1	CT2	S	Wet	Ap	0-15	8.4	0.23	1.61	0.12	13.14	5.37	0.64	0.97	1.84	1.32	32.19	35.16	32.65			
CU1	CT2	S	Wet	Bt1	15-43	8.2	0.34	1.41	0.11	13.42	3.24	0.39	1.02	1.94	1.29	28.76	37.49	33.74			
CU1	CT2	S	Wet	Bt2	43-76	8.3	0.43	1.74	0.13	13.88	4.73	0.57	1.17	2.22	1.23	14.22	46.09	39.69			
CU1	CT2	S	Wet	Btk	76-114	8	0.89	1.58	0.09	16.75	7.72	0.93	0.65	1.24	1.28	21.34	42.45	36.21			
CU1	CT2	S	Wet	BC	114+	8.2	0.42	0.86	0.07	13.14	4.22	0.51	0.35	0.67	1.45	38.14	37.11	24.74			
CU1	ST1	N	Wet	Ap	0-22	8.2	0.46	1.51	0.13	12.11	4.44	0.53	0.98	1.86	1.33	34.04	37.33	28.62			
CU1	ST1	N	Wet	Btk	22-44	8.3	0.31	1.60	0.11	14.89	6.84	0.82	0.78	1.49	1.47	57.26	26.62	16.11			
CU1	ST1	N	Wet	Bt1	44-78	8.1	0.49	0.70	0.07	10.60	2.44	0.29	0.41	0.77	1.56	66.94	21.10	11.96			
CU1	ST1	N	Wet	Bt2	78-116	8.4	0.32	0.60	0.05	11.85	2.57	0.31	0.30	0.56	1.52	46.41	34.89	18.69			
CU1	ST1	N	Wet	BC	116-150+	8.2	0.41	0.88	0.05	18.18	5.62	0.67	0.20	0.38	1.54	46.59	34.78	18.63			
CU1	ST1	S	Wet	Ap	0-15	8.4	0.27	1.58	0.14	11.61	4.06	0.49	1.10	2.08	1.23	23.26	37.70	39.04			
CU1	ST1	S	Wet	Bt1	15-45	8.3	0.41	1.34	0.11	11.83	4.05	0.49	0.86	1.63	1.33	30.14	38.10	31.75			
CU1	ST1	S	Wet	Btk	45-75	8.2	0.54	1.61	0.11	14.31	6.16	0.74	0.87	1.65	1.28	23.17	54.69	22.14			
CU1	ST1	S	Wet	Bt2	75-102	7.9	1.12	1.41	0.10	13.86	5.35	0.64	0.76	1.45	1.31	24.85	50.95	24.20			
CU1	ST1	S	Wet	BC	102-150+	8.1	0.61	0.87	0.08	11.41	3.18	0.38	0.48	0.92	1.37	29.64	46.05	24.30			
CU1	ST2	N	Wet	Ap	0-10	8.1	0.43	1.72	0.14	12.33	5.03	0.60	1.12	2.12	1.39	46.74	32.97	20.29			
CU1	ST2	N	Wet	Btk1	10-31	8.3	0.3	1.98	0.13	15.75	8.08	0.97	1.01	1.91	1.29	28.58	38.26	33.16			
CU1	ST2	N	Wet	Btk2	31-57	8.4	0.36	1.92	0.10	19.49	9.66	1.16	0.76	1.45	1.27	21.24	43.19	35.57			
CU1	ST2	N	Wet	Bt	57-100	8.6	0.22	0.78	0.07	10.89	2.60	0.31	0.47	0.89	1.48	45.49	32.96	21.55			
CU1	ST2	N	Wet	BCk	100+	8.2	0.52	1.03	0.05	18.92	5.96	0.71	0.31	0.60	1.52	48.09	35.45	16.46			
CU1	ST2	S	Wet	Ap	0-15	8.3	0.26	1.95	0.16	12.52	4.96	0.60	1.35	2.57	1.26	29.65	38.37	31.98	37.15	21.11	16.04
CU1	ST2	S	Wet	Bt1	15-45	8.3	0.35	1.47	0.12	12.40	4.86	0.58	0.89	1.69	1.38	32.70	38.09	29.20	30.13	21.30	8.83
CU1	ST2	S	Wet	Bt2	45-60	8.3	0.32	1.07	0.08	12.74	3.86	0.46	0.61	1.16	1.40	35.63	51.75	12.62	36.36	17.77	18.58
CU1	ST2	S	Wet	Btk1	60-94	8.3	0.42	1.81	0.13	13.80	6.22	0.75	1.06	2.02	1.24	13.60	43.85	42.56	35.64	24.85	10.79
CU1	ST2	S	Wet	BCk	94-119	8.3	0.27	2.33	0.10	22.80	12.88	1.55	0.78	1.49	1.26	15.53	40.34	44.12	42.48	24.10	18.38
N1	-	-	-	A	0-9	8	0.33	3.94	0.22	17.91		0.06	3.88	7.36	0.99	22.00	39.00	39.00	39.1	20.4	18.7
N1	-	-	-	BA	9-26	8.2	0.18	3.92	0.19	20.85		0.07	3.85	7.31	0.98	22.00	37.00	42.00	34.1	16.2	17.9
N1	-	-	-	Bt1	26-51	8.2	0.3	3.74	0.14	25.97		0.08	3.66	6.96	1.00	19.00	39.00	42.00	25	17.4	7.7
N1	-	-	-	Bt2	51-75	8.3	0.12	2.99	0.14	21.51		0.05	2.94	5.59	1.05	16.00	39.00	45.00	25.2	17.7	7.5
N1	-	-	-	Bt3	75-95	8.4	0.15	3.02	0.10	31.79		0.08	2.94	5.60	1.06	22.00	41.00	36.00	32.6	21.9	10.6
N1	-	-	-	BCk	95-106	8.5	0.14	3.26	0.08	42.89		0.08	3.18	6.03	1.09	31.00	38.00	31.00	29.3	16.4	12.9
N1	-	-	-	Ck	106+	7.7	2.06	1.85	0.04	51.39		0.06	1.79	3.40	1.30	49.00	28.00	23.00	26.5	11.3	15.2

Table 2.4. Soil Chemical properties for site CU2 and N2 in the South Platte Basin.

Site	Treatment	Field Loc	Furrow Type	Horizon	Depth (cm)	pH	EC	TC	TN	C:N	Total $CaCO_3$	TOIC	TOC	OM %	ρb	Sand %	Clay %	Silt %	Field Cap	Wilt Point	AWC
CU2	CT1	N	Wet	Ap1	0-29	8.3	0.23	1.63	0.12	14.04	4.07	0.49	1.14	2.17	1.25	23.18	44.07	32.74	28	20.1	7.9
CU2	CT1	N	Wet	Ap2	29-52	8.6	0.14	1.20	0.06	21.42	6.59	0.79	0.41	0.77	1.50	35.37	32.95	31.68	28.5	20.2	8.3
CU2	CT1	N	Wet	Bk1	52-93	8.2	0.21	0.85	0.04	23.77	5.90	0.71	0.14	0.27	1.43	33.45	28.88	37.67	18.3	11.2	7.1
CU2	CT1	N	Wet	Bk2	93-127	8.6	0.17	0.90	0.03	32.56	5.76	0.69	0.21	0.40	1.41	33.29	27.69	39.02	24.5	16	8.5
CU2	CT1	N	Wet	Bk3	127+	8.3	0.2	0.80	0.02	33.45	6.62	0.79	0.00	0.00	1.27	20.01	24.12	55.86	29.3	22	7.3
CU2	CT1	S	Wet	Ap1	0-28	8.5	0.13	1.27	0.10	13.03	2.91	0.35	0.92	1.75	1.36	38.12	36.62	25.26			
CU2	CT1	S	Wet	Ap2	28-47	8.2	0.21	1.00	0.04	23.17	5.82	0.70	0.31	0.58	1.48	43.63	27.56	28.81			
CU2	CT1	S	Wet	Bk1	47-89	8.8	0.13	0.93	0.03	34.05	6.61	0.79	0.14	0.26	1.44	35.87	26.41	37.72			
CU2	CT1	S	Wet	Bk2	89-135	8.6	0.18	0.90	0.03	32.92	7.64	0.92	-0.02	-0.03	1.39	29.18	25.29	45.53			
CU2	CT1	S	Wet	Bk3	135+	8.5	0.21	1.46	0.03	44.59	8.78	1.05	0.41	0.77	1.42	40.54	29.10	30.36			
CU2	CT2	N	Wet	Ap1	0-31	8.4	0.16	1.49	0.10	14.58	4.47	0.54	0.95	1.81	1.29	29.15	37.29	33.56			
CU2	CT2	N	Wet	Ap2	31-44	8.6	0.16	1.06	0.04	23.56	6.74	0.81	0.25	0.48	1.47	38.64	32.56	28.80			
CU2	CT2	N	Wet	Bk1	44-81	8.5	0.17	0.95	0.04	26.78	6.17	0.74	0.21	0.39	1.51	48.53	25.11	26.36			
CU2	CT2	N	Wet	Bk2	81-120	9	0.12	0.90	0.03	35.79	7.51	0.90	0.00	-0.01	1.57	45.66	22.75	31.59			
CU2	CT2	N	Wet	Bk3	120+	8.3	0.21	0.89	0.03	35.09	6.63	0.80	0.10	0.19	1.34	27.99	22.74	49.27			
CU2	CT2	S	Wet	Ap1	0-23	8.3	0.22	2.45	0.16	15.23	4.62	0.55	1.90	3.60	1.15	16.75	46.11	37.14			
CU2	CT2	S	Wet	Ap2	23-47	8.2	0.34	1.54	0.10	15.41	4.28	0.51	1.03	1.96	1.25	21.99	43.48	34.53			
CU2	CT2	S	Wet	Bk1	47-90	8.6	0.13	1.08	0.05	21.47	6.18	0.74	0.33	0.64	1.50	48.17	27.81	24.02			
CU2	CT2	S	Wet	Bk2	90-127	8.4	0.19	1.06	0.04	28.78	6.66	0.80	0.26	0.49	1.49	47.41	25.04	27.55			
CU2	CT2	S	Wet	Bk3	127+	8.8	0.12	0.91	0.03	34.90	7.81	0.94	-0.03	-0.06	1.44	33.49	25.10	41.41			
CU2	ST1	N	Wet	Ap1	0-30	8.3	0.21	1.51	0.11	14.03	2.16	0.26	1.25	2.38	1.23	23.12	40.33	36.55			
CU2	ST1	N	Wet	Ap2	30-61	8.6	0.14	1.81	0.09	19.10	6.23	0.75	1.06	2.02	1.37	43.11	30.34	26.55			
CU2	ST1	N	Wet	Bk1	61-93	8.4	0.22	1.12	0.03	32.22	8.07	0.97	0.15	0.28	1.43	35.68	25.22	39.10			
CU2	ST1	N	Wet	Bk2	93-125	9	0.11	0.80	0.03	31.50	7.08	0.85	-0.05	-0.10	1.50	40.94	22.62	36.44			
CU2	ST1	N	Wet	Bk3	125+	8.6	0.17	0.80	0.03	30.04	6.98	0.84	-0.04	-0.08	1.29	23.06	22.34	54.60			
CU2	ST1	S	Wet	Ap1	0-35	8.4	0.12	1.36	0.11	12.76	3.35	0.40	0.96	1.82	1.29	28.04	40.40	31.56			
CU2	ST1	S	Wet	Ap2	35-51	8.2	0.24	0.79	0.05	16.83	3.99	0.48	0.31	0.58	1.49	43.61	27.57	28.82			
CU2	ST1	S	Wet	Bk1	51-90	8.5	0.15	0.71	0.03	22.99	4.98	0.60	0.11	0.21	1.50	44.76	25.11	30.13			
CU2	ST1	S	Wet	Bk2	90-128	8.4	0.21	0.73	0.02	29.10	5.85	0.70	0.02	0.05	1.40	32.24	22.59	45.17			
CU2	ST1	S	Wet	Bk3	128+	8.6	0.13	0.91	0.03	34.57	7.53	0.90	0.01	0.01	1.50	38.30	30.22	31.48			
CU2	ST2	N	Wet	Ap1	0-30	8.3	0.19	1.38	0.10	14.04	3.79	0.46	0.93	1.76	1.35	34.79	38.36	26.85			
CU2	ST2	N	Wet	Ap2	30-57	8.3	0.17	0.87	0.05	19.14	5.27	0.63	0.24	0.46	1.50	43.29	27.72	28.98			
CU2	ST2	N	Wet	Bk1	57-91	8.3	0.19	0.84	0.04	23.10	5.91	0.71	0.13	0.25	1.50	44.81	25.09	30.11			
CU2	ST2	N	Wet	Bk2	91-127	8.7	0.11	0.80	0.03	30.52	7.02	0.84	-0.05	-0.09	1.48	38.26	25.20	36.54			
CU2	ST2	N	Wet	Bk3	127+	8.5	0.17	0.95	0.03	36.72	7.29	0.88	0.07	0.13	1.28	24.02	25.33	50.66			
CU2	ST2	S	Wet	Ap1	0-36	8.3	0.13	1.77	0.11	16.53	3.87	0.46	1.31	2.48	1.23	23.42	43.39	33.18	35.1	24.7	10.4
CU2	ST2	S	Wet	Ap2	36-53	8.2	0.23	0.94	0.05	17.61	5.31	0.64	0.30	0.57	1.50	45.64	30.34	24.02	22.5	14.8	7.7
CU2	ST2	S	Wet	Bk1	53-92	8.5	0.14	1.03	0.04	25.68	6.84	0.82	0.21	0.40	1.49	45.37	25.41	29.22	29.9	19.7	10.2
CU2	ST2	S	Wet	Bk2	92-130	8.3	0.2	0.85	0.03	30.75	7.22	0.87	-0.01	-0.03	1.48	36.73	30.37	32.90	30.1	18.9	11.1
CU2	ST2	S	Wet	Bk3	130+	8.5	0.15	1.03	0.03	35.95	8.73	1.05	-0.02	-0.03	1.48	38.60	25.06	36.34	30.3	19.6	10.8
N2	-	-	-	A	0-13	8.1	0.3	2.93	0.19	15.50		0.03	2.90	5.50	1.12	34.00	43.00	23.00	28.6		
N2	-	-	-	A	13-34	8.3	0.28	2.04	0.12	17.14		0.03	2.01	3.82	1.20	31.00	41.00	28.00	37.3	25.4	12
N2	-	-	-	Btk1	34-64	8.3	0.62	1.85	0.05	38.54		0.05	1.80	3.42	1.26	37.00	38.00	25.00	27.6	19.6	8
N2	-	-	-	Bk1	64-85	8.7	0.45	2.12	0.04	51.71		0.05	2.07	3.93	1.23	39.00	35.00	25.00	34.4	15.7	18.8
N2	-	-	-	Bk2	85-120	8.2	1.16	2.75	0.03	105.77		0.08	2.67	5.07	1.19	49.00	23.00	28.00	24.3	12.2	12.2
N2	-	-	-	Bk3	120+	8.4	0.79	3.34	0.02	151.82		0.09	3.25	6.17	1.14	50.00	23.00	28.00	17.5	11.2	6.3

The pH profiles across all sites show generally neutral to slightly alkaline conditions, with most values ranging between 7.5 and 8.5. The CU1 and CU2 sites exhibit relatively stable pH across depth, with minor fluctuations between treatments. In contrast, N1 and N2 display slightly more variation in pH with depth, particularly in the upper horizons. Across all profiles, no drastic pH shifts are observed with depth or treatment, suggesting relatively uniform chemical conditions within the profiles sampled (Figures 2.9 and 2.10).

ARDEC

Carbonate

The calcium carbonate data for CU1 soils are shown in Figure 2.5A. Calcium carbonate generally exhibited an increase with depth across all treatments and field positions. The depth to the zone of maximum carbonate accumulation in this soil occurs around 100-150cm in the fine shale and sandstone fine-textured soil. The average total pedon calcium carbonate equivalent is 1073 g/cm^3 to a depth of 150cm. Compared to the coarser-textured soil at CU2, the average carbonate equivalent is 20.5% lower. No treatment level differences were detected in vertical carbonate distribution.

AWC

Soil moisture characteristics varied notably by treatment and depth. Mean AWC at CU1 and N1 is 11.3% and 13%, respectively (Figure 2.5 B). The ST2 treatment consistently exhibited the highest Field Capacity (FC) and Available Water Capacity (AWC) across all depths, indicating improved soil water retention. In contrast, CT1 showed the lowest values for both FC and AWC, suggesting reduced water-holding capacity, potentially due to soil compaction. Native treatments (N1 and N2) displayed more variable profiles, with higher AWC in surface layers and notable fluctuations at deeper depths. These results highlight the differences in soil AWC under ST treatments across both watersheds.

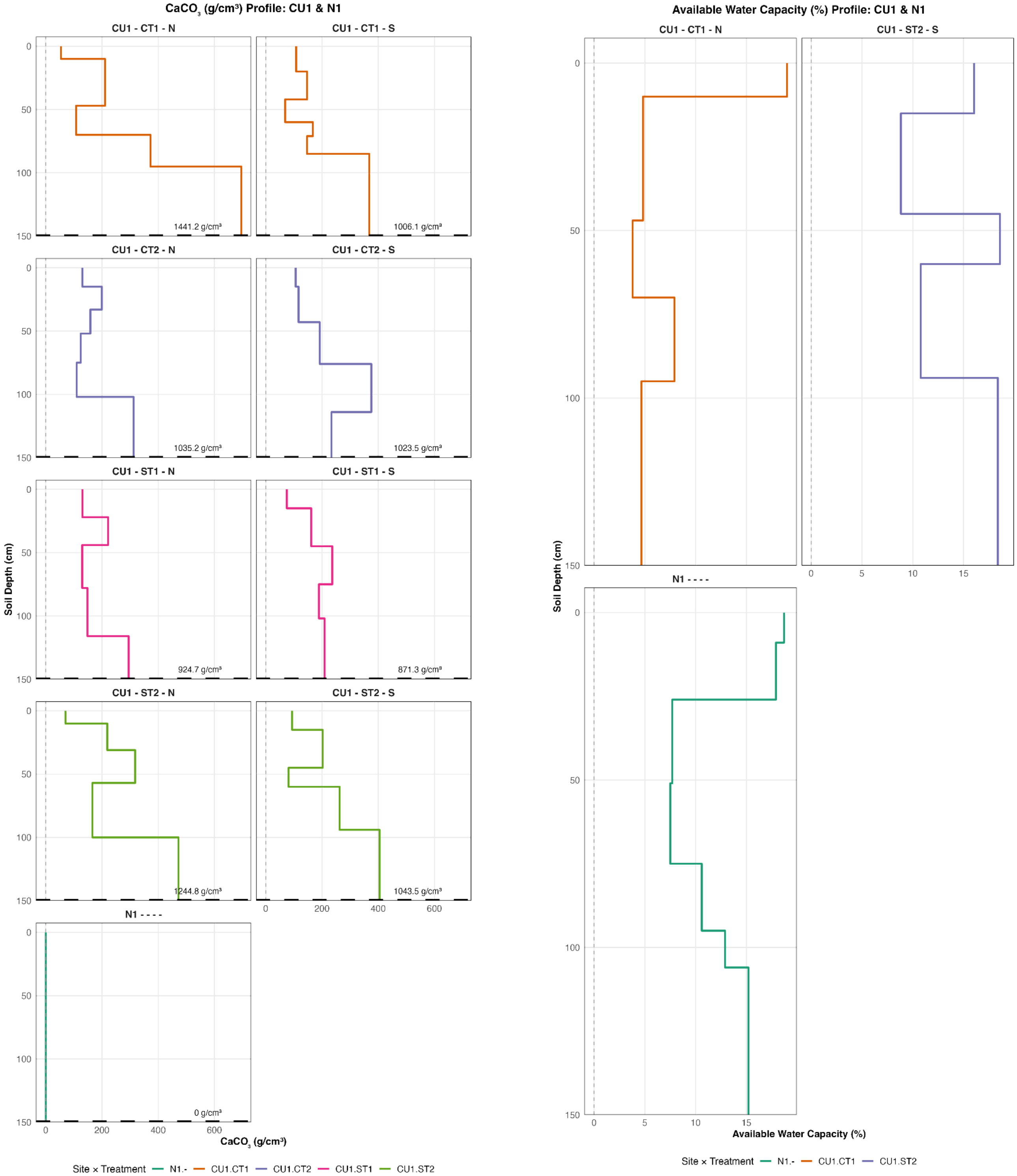


Figure 2.5. (A - left) Total CaCO₃ equivalent as a function of soil depth for CU1 conventional tillage (CT) and strip tillage (ST) treatments at the north and south field positions (N and S). (B - right) Available water capacity (AWC) as a function of soil depth for the same treatments and positions. The native site (N1) is included for comparison.

OM

The content and vertical distribution of organic matter for CU1 are shown in Figure 2.6. Generally, higher levels of organic matter occur near the surface where plant residue additions and root production are more prevalent. Irrespective of treatment, organic matter equivalent was highest near 10-50cm (40cm), followed by a progressive decrease with profile depth. The average organic matter equivalent at CU1 is 68% higher overall than that of the Arkansas basin agricultural soil, CU2. Management has a profound impact on total organic matter content throughout the profile. Native site 1 (N1) is approximately 260% higher in average OM equivalent to a depth of 150cm than the corresponding cultivated site in the South Platte basin. Significant treatment level differences were not detected in organic matter equivalence across both sites.

C:N Ratio

Carbon to nitrogen ratios as a function of soil depth are displayed in Table 2.5. Generally, soils with carbon to nitrogen ratios less than or equal to 20:1 yield net mineralization via microbial processes, thereby increasing overall plant available nitrogen and increasing potential for N leaching. Soils with carbon-to-nitrogen ratios greater than or equal to 30:1 exhibit net immobilization, thereby reducing plant-available nitrogen and reducing the risk of N leaching. The vertical trends in C:N ratios at CU1 generally remained consistent throughout the profile, with minor increases occurring between 100-150cm depth. Generally, C:N remained below 20:1, suggesting CU1 has an increased mineralization potential. Surface horizons at Native site N1 remained above 30:1 (net immobilization) and increased with profile depth, indicating the effect of management on the C:N ratio. No treatment level differences were detected within CU1.

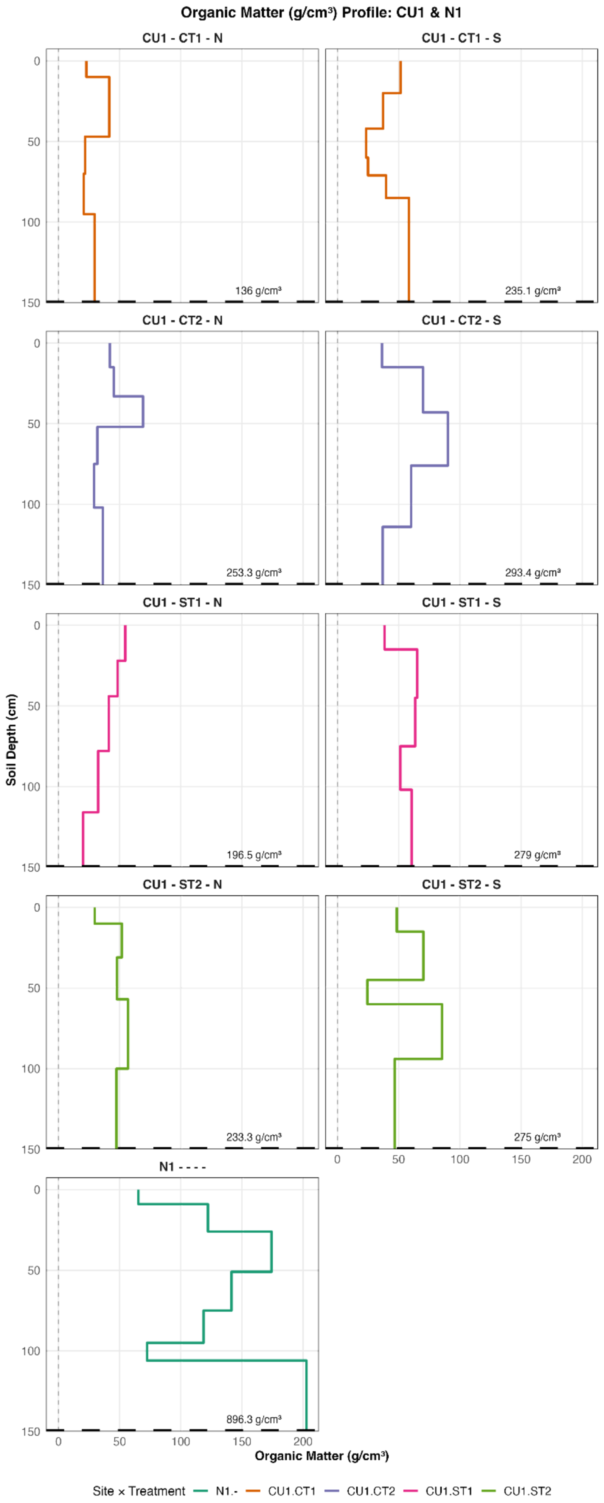


Figure 2.6. Total Organic Matter equivalent as a function of soil depth for CU1 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N1 the corresponding native site is included.

Table 2.5. C:N ratios by soil depth for CU1 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N1 the corresponding native site is included.

South Platte Basin C:N Ratios (CU1, N1)

Site	Treatment	Field Location	Soil Depth (cm)	C:N Ratio
CU1	CT1	N	0-10	13.64646
CU1	CT1	N	10-47	14.27045
CU1	CT1	N	47-70	13.03108
CU1	CT1	N	70-95	33.07997
CU1	CT1	N	95-150	33.18442
CU1	CT1	S	0-20	11.54422
CU1	CT1	S	20-42	13.80150
CU1	CT1	S	42-60	10.96745
CU1	CT1	S	60-71	18.31795
CU1	CT1	S	71-85	14.67358
CU1	CT1	S	85-150	18.28851
CU1	CT2	N	0-15	14.61867
CU1	CT2	N	15-33	16.00560
CU1	CT2	N	33-52	23.70315
CU1	CT2	N	52-75	12.80451
CU1	CT2	N	75-102	11.13273
CU1	CT2	N	102-150	15.17474
CU1	CT2	S	0-15	13.14413
CU1	CT2	S	15-43	13.42064
CU1	CT2	S	43-76	13.88309
CU1	CT2	S	76-114	16.74835
CU1	CT2	S	114-150	13.14030
CU1	ST1	N	0-22	12.10830
CU1	ST1	N	22-44	14.88680
CU1	ST1	N	44-78	10.59603
CU1	ST1	N	78-116	11.84926
CU1	ST1	N	116-150	18.18091
CU1	ST1	S	0-15	11.61169
CU1	ST1	S	15-45	11.82623
CU1	ST1	S	45-75	14.31304
CU1	ST1	S	75-102	13.85722
CU1	ST1	S	102-150	11.40805
CU1	ST2	N	0-10	12.32514
CU1	ST2	N	10-31	15.74884
CU1	ST2	N	31-57	19.48903
CU1	ST2	N	57-100	10.89000
CU1	ST2	N	100-150	18.91716
CU1	ST2	S	0-15	12.51919
CU1	ST2	S	15-45	12.39731
CU1	ST2	S	45-60	12.74099
CU1	ST2	S	60-94	13.80187
CU1	ST2	S	94-150	22.79778
N1	-	-	0-9	17.90909
N1	-	-	9-26	20.85106
N1	-	-	26-51	25.97222
N1	-	-	51-75	21.51079
N1	-	-	75-95	31.78947
N1	-	-	95-106	42.89474
N1	-	-	106-150	51.38889

AVRC

Carbonate

The calcium carbonate data for CU2 soils are shown in Figure 2.7 A. The depth to the zone of maximum carbonate accumulation reflects the soil's leaching and permeability characteristics. This zone occurs from 50 - 125cm (75cm thick) depth. The average calcium carbonate equivalent is 1,293 g/cm^3 to a depth of 150cm. The limestone, shale, and alluvial-deposited parent material soil are, on average, 20.5% higher in calcium carbonate equivalent than the fine-textured shale and sandstone parent material soil at CU1. There were no significant treatment-level differences within or across sites.

Both soils are moderately enriched and rich in carbonate, but differences in parent material reflect the degree of leaching and permeability differences between them. These contrasts point towards the distinct hydrological behavior within each basin.

AWC

Mean AWC at CU2 and N2 is 9% and 11.5%, respectively (Figure 2.7 B). The ST2 treatment consistently exhibited the highest Field Capacity (FC) and Available Water Capacity (AWC) across all depths, indicating improved soil water retention. In contrast, CT1 showed the lowest values for both FC and AWC, suggesting reduced water-holding capacity, potentially due to soil compaction. Native treatments (N1 and N2) displayed more variable profiles, with higher AWC in surface layers and notable fluctuations at deeper depths. These results highlight the differences in soil AWC under ST treatments across both watersheds.

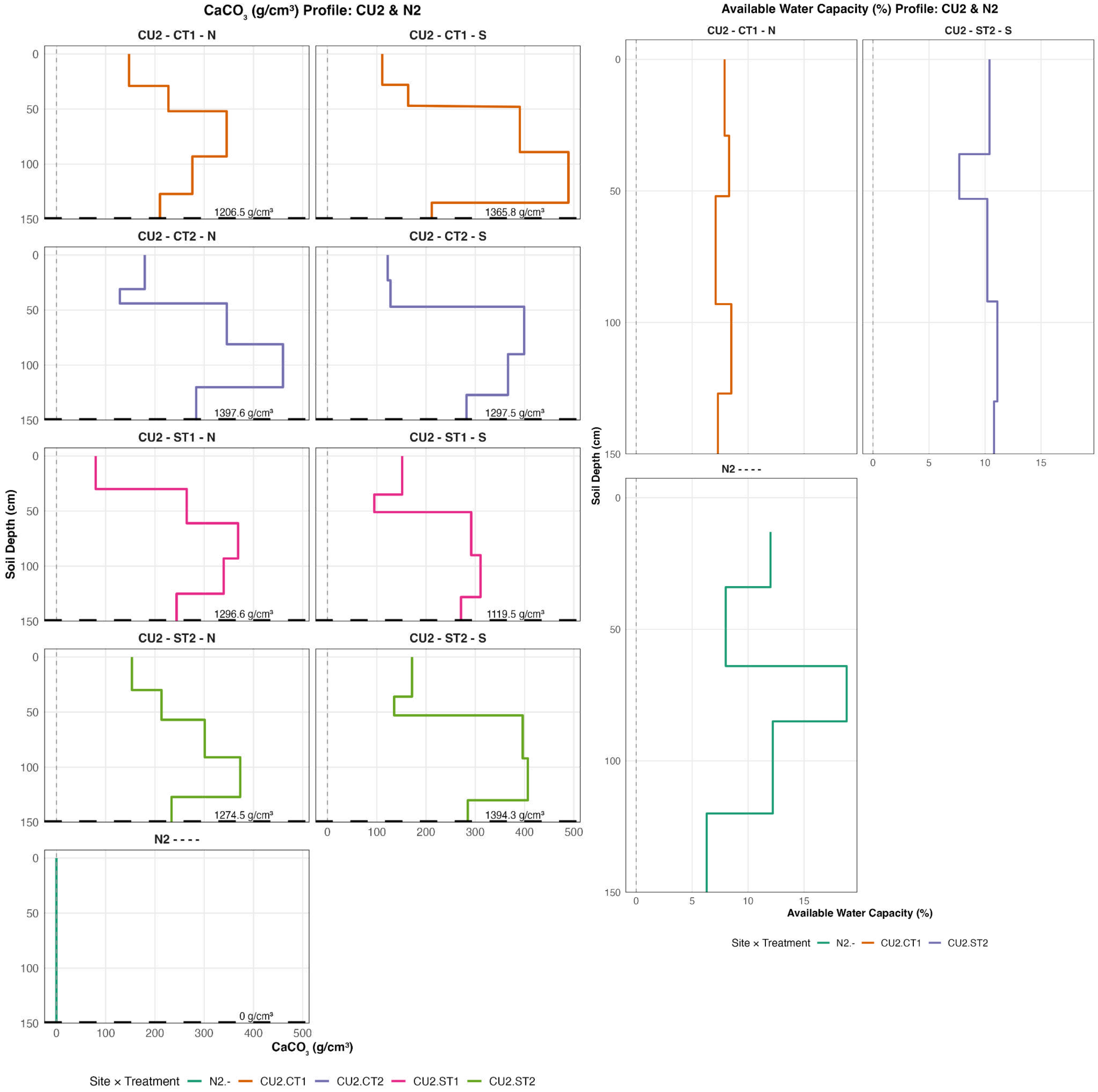


Figure 2.7. (A - left) Total CaCO₃ equivalent as a function of soil depth for CU2 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). (B - right) AWC as a function of soil depth for CU2 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N2 the corresponding native site is included.

OM

The content and vertical distribution of organic matter for CU2 are shown in Figure 2.8. Organic matter distribution in the coarse textured limestone, shale, and alluvial parent material shows a more uniform decrease with depth than in CU1. Native site 2 (N2) is approximately 500% higher in average OM equivalent to a depth of 150cm than the corresponding cultivated site in the Arkansas basin. Significant treatment level differences were not detected in organic matter equivalence across both sites.

C:N Ratio

Carbon to nitrogen ratios as a function of soil depth are displayed in Table 2.6. The vertical trends in C:N ratios across most samples at CU2 in the first two horizons (0-50cm) remained below 20:1, suggesting an increased mineralization potential in this zone. Subsequent horizons C:N ratios increased with profile depth, beginning at 30:1, indicating increased immobilization potential. Surface horizons at Native site N1 remained below 20:1 (net mineralization) and increased with profile depth well above 30:1, suggesting the effect management has on the C:N ratio. No treatment level differences were detected within CU2.

Soils at CU1 exhibit characteristics that favor net mineralization, whereas those at CU2 favor net immobilization. Within the South Platte Basin system (CU1), management practices appear to lower C:N ratios, promoting mineralization pathways and the release of available nitrogen. Conversely, in the Arkansas Basin system (CU2), management appears to increase C:N ratios with depth, often exceeding 30:1 and substantially higher than typical cultivated systems, thereby promoting strong immobilization dynamics and limiting nitrate availability.

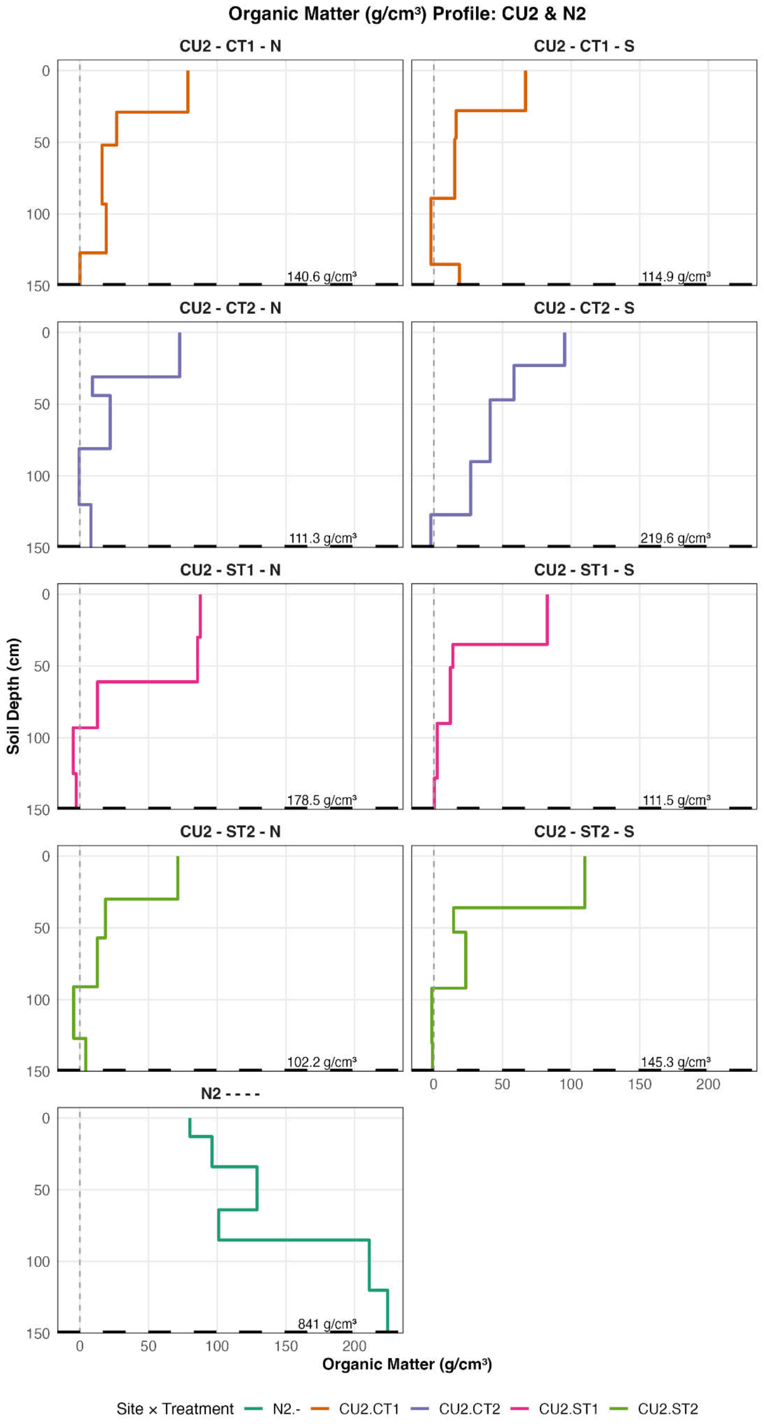


Figure 2.8. Total Organic Matter equivalent as a function of soil depth for CU2 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N2 the corresponding native site is included.

Table 2.6. C:N ratios by soil depth for CU1 conventional tillage (CT) and strip tillage (ST) treatments at the north and south ends of the field (N & S). N1 the corresponding native site is included.

Arkansas Basin C:N Ratios by Site (CU2, N2)

Site	Treatment	Field Location	Soil Depth	C:N Ratio (unitless)
CU2	CT1	N	0-29	14.04343
CU2	CT1	N	29-52	21.41694
CU2	CT1	N	52-93	23.76772
CU2	CT1	N	93-127	32.55726
CU2	CT1	N	127-150	33.45240
CU2	CT1	S	0-28	13.03332
CU2	CT1	S	28-47	23.16861
CU2	CT1	S	48-89	34.04988
CU2	CT1	S	89-135	32.92166
CU2	CT1	S	135-150	44.59151
CU2	CT2	N	0-31	14.58299
CU2	CT2	N	31-44	23.56275
CU2	CT2	N	44-81	26.78278
CU2	CT2	N	81-120	35.79352
CU2	CT2	N	120-150	35.08871
CU2	CT2	S	0-23	15.23199
CU2	CT2	S	23-47	15.40858
CU2	CT2	S	47-90	21.47245
CU2	CT2	S	90-127	28.78212
CU2	CT2	S	127-150	34.89906
CU2	ST1	N	0-30	14.02858
CU2	ST1	N	30-61	19.10292
CU2	ST1	N	61-93	32.21865
CU2	ST1	N	93-125	31.49562
CU2	ST1	N	125-150	30.03534
CU2	ST1	S	0-35	12.75963
CU2	ST1	S	35-51	16.83216
CU2	ST1	S	51-90	22.98772
CU2	ST1	S	90-128	29.10153
CU2	ST1	S	128-150	34.57295
CU2	ST2	N	0-30	14.04142
CU2	ST2	N	30-57	19.14334
CU2	ST2	N	57-91	23.10386
CU2	ST2	N	91-127	30.52098
CU2	ST2	N	127-150	36.72095
CU2	ST2	S	0-36	16.52581
CU2	ST2	S	36-53	17.61198
CU2	ST2	S	53-92	25.67921
CU2	ST2	S	92-130	30.74589
CU2	ST2	S	130-150	35.94998
N2	-	-	0-13	15.50265
N2	-	-	13-34	17.14286
N2	-	-	34-64	38.54167
N2	-	-	64-85	51.70732
N2	-	-	85-120	105.76923
N2	-	-	120-150	151.81818

3.4 DISCUSSION

Previous research has shown that drivers of nitrate contamination in Colorado Piedmont agricultural regions vary across spatial scales. While regional-scale vulnerability is influenced by factors such as depth to groundwater, soil drainage (texture and slope), land use, and recharge potential, contamination has occurred in areas not classified as vulnerable, and not all high-risk areas show contamination. These discrepancies highlight the importance of assessing leaching risk at the field scale. Ultimately, it is nitrogen management that determines the extent of leaching, though site-specific leaching potential also depends on soil properties, irrigation practices, and climatic conditions (Bauder et al., 2011). In Colorado agricultural soils, our understanding of fundamental soil properties driving nitrate leaching is improving but remains incomplete, especially at finer spatial scales.

Irrigation water quality contrasts between basins exhibit a strong influence on soil properties within each system. In the Arkansas Basin, irrigation water contains soluble gypsum, resulting in high salinity or sodium levels that can promote clay dispersion, leading to surface sealing, increased bulk density, and reduced porosity. In contrast, calcium resulting from the dispersion of gypsum and found in irrigation water can improve soil structure by enhancing supporting flocculation and aggregate stability.

Carbonate minerals, on the other hand, are much less soluble and tend to accumulate in arid and semi-arid soils. Their precipitation can restrict infiltration and root penetration, contributing to reduced porosity and localized compaction. Together, the balance between gypsum dissolution and carbonate accumulation under varying irrigation water practices is tightly coupled with the long-term structural integrity and hydrologic behavior of cultivated soils.

The results across all sites indicate that pedogenic development plays a significant role in shaping soil hydrology and, consequently, nitrate leaching potential. At the South Platte Basin, the soils examined and soil properties measured demonstrate some key characteristics likely acting as key contributors in fluid flow and nitrate leaching potential. First, CU1 and N1 are older soils relative to CU2/N2. This implies these soils show signs of greater pedogenic development from soil-forming processes, and these properties influence water flow and leaching potential dynamics. First, the argillic horizon present at CU1 (~45-75cm) from illuviation has high porosity and significant water holding potential, likely lowering the potential for nitrate to leach. The pores in the clay band are extremely fine compared to the pores in the overlying layers due to the ability of the argillic horizon to prevent downward penetration of water. The rate of water transmission in the argillic horizon is decreased in these layers and may inhibit the flow of water. At the Arkansas Valley sites, across treatments and locations within CU2, a clay band from 0 to 45 cm was a notable feature. This layer likely contributed to reducing deep nitrate leaching, while also increasing the potential for surface runoff due to the clay's high water-holding capacity.

At CU1, a plow pan was observed between 0–15 cm, marked by increased aggregate firmness. This layer likely influences nitrate leaching dynamics, as repeated tillage disrupts soil structure and reduces organic matter, thereby diminishing macroporosity and water-holding capacity. This compaction of soil leads to decreased pore space, permeability, and drainage, increasing surface runoff during precipitation or irrigation. These effects are amplified under dry initial conditions, as partially saturated soils exhibit better infiltration than soils near the wilting point. In contrast, the plow pan at CU2 was thicker (0–50 cm) and exhibited very firm aggregate consistency, likely due to compaction. The increased depth and reduced permeability may limit nitrate leaching but further promote surface runoff. Overall, while long-term tillage may reduce deep nitrate leaching by impeding infiltration, it likely increases surface solute runoff due to compaction and reduced permeability near the surface. At both native sites, significantly lower bulk density was observed throughout the pedon, suggesting better soil structure and greater permeability, pointing towards an increased potential for leaching in the native systems.

Texture and color act as indicators of porosity and organic matter content, respectively, both of which are critical in controlling microporosity, regulating fluid movement, and determining soil water-holding capacity. Soil texture influences water flow primarily by affecting pore size distribution, infiltration rates, and water retention. Fine-textured soils, like clays, contain smaller pores that slow infiltration and enhance water retention, which can reduce nitrate leaching by holding water and dissolved nutrients in the root zone longer. As an inherent property defined by mineral particle size, texture is not expected to change significantly with tillage or other management practices. Across all sites, soils are predominantly fine-textured, with loams and clays prevailing throughout the profile. These textures indicate high porosity and substantial water-holding capacity, though a portion of the water is retained tightly within micropores. As a result, vertical water movement is slowed, which lowers the risk of nitrate leaching compared to coarser soils. Finer - textured soils characteristic of the South Platte basin, relative to those in the Arkansas Basin, exhibit greater water holding capacity and longer retention times, which collectively promote nitrate retention within the profile.

Additionally, all sites are classified as Mollisols as the soil order is distinguished by high base saturation and the presence of thick, dark surface horizons that are enriched in organic matter relative to other horizons in the profile. These organic matter-rich surface horizons increase the soil's water-holding capacity by reducing bulk density and increasing microporosity, which allows them to retain water more tightly because it is retained by capillary forces. As a result, water movement through these layers is expected to be slowed, which likely reduces the rate of percolation and influences the soil's potential to leach nitrate, either by limiting downward nitrate movement or promoting longer residence times in the root zone, especially in the upper soil profile where organic matter is most concentrated. Organic matter is widely recognized as a key driver in the development and stabilization of soil structure and is likely one of the most critical factors influencing nitrate leaching potential in these systems (Fukumasu et al., 2024).

The dominance of fine-textured soils (loams and clays) with subangular blocky structure in both systems has significant implications for water movement and nitrate leaching. Fine-textured soils inherently possess high microporosity and mesoporosity, which contribute to elevated water retention and slow infiltration rates. When combined with subangular blocky structure, water movement becomes more tortuous due to the arrangement of angular aggregates and reduced continuity of macropore networks.

Under near-saturated conditions, this structural configuration favors matrix flow over preferential flow, thereby reducing the likelihood of rapid nitrate leaching (Fukumasu et al., 2024). The slower percolation through smaller pores allows for greater interaction between water and soil particles, increasing the residence time of nitrate within the root zone and enhancing the opportunity for plant uptake. As a result, nitrate leaching risk is generally lower in these systems, provided soils are not compacted or subject to prolonged saturation that could activate deeper macropore pathways. Overall, the structural and textural properties of these soils play a key role in moderating nitrate fate and transport.

At CU1, the combination of fine-textured soils, an organic matter–rich mollic epipedon, high AWC, and an underlying argillic horizon contributes to a profile that is generally resistant to nitrate leaching under typical conditions. The subangular blocky structure throughout the profile produces tortuous flow paths and moderate macropore connectivity, which limits rapid water movement and promotes matrix-dominated flow. The mollic epipedon enhances water retention and supports biological activity, increasing the potential of nitrate uptake or immobilization. AWC data corroborates this finding, showing relatively high water-holding capacity at CU1 (mean AWC: 11.3%), with elevated values in the ST2 and N1 profiles. These conditions increase nitrate residence time in the root zone, giving plants and microbes more opportunity to retain or transform nitrogen before it moves deeper into the profile. The clay-rich argillic horizon acts as a permeability barrier, slowing vertical flow and potentially causing perched water above this layer, while the presence of massive structure at depths exceeding 100 cm may further impede downward movement. These characteristics collectively suggest a lower risk of nitrate leaching at CU1, except under high-intensity rainfall or irrigation events where temporary saturation may activate bypass pathways. Overall, nitrate dynamics at this site are likely governed by slow percolation, increased residence time, and enhanced interaction with the soil matrix. When coupled with the low C:N ratios that promote net nitrate production, these hydrologic properties create a system that favors nitrate formation but limits its downward mobility. As a result, nitrate tends to remain available within the root zone, supporting plant uptake, while leaching losses to deeper horizons are minimized, effectively retaining nitrate within the profile.

At CU2, the presence of granular structure within a clay-rich mollic epipedon yields a unique combination of high surface porosity, elevated organic matter, and fine subsoil texture, though generally more coarse textured overall compared to CU1. Granular structure in the A horizon enhances water infiltration, allowing nitrate to move rapidly into the upper soil profile. However, the underlying clay-rich horizon slows percolation and promotes water retention, potentially causing water and solutes to accumulate or move laterally along horizon boundaries. The high organic matter content within the mollic epipedon further improves microporosity and nitrogen retention through increased microbial activity and cation exchange capacity. Within this surface horizon, relatively low C:N ratios indicate conditions favorable for net mineralization, whereas the higher C:N ratios observed in subsequent horizons suggest a shift toward net immobilization at depth, lowering the leaching potential below the root zone. Despite these beneficial structural and compositional features, CU2 exhibited lower overall AWC (mean: 9%) compared to CU1, suggesting less capacity to store water. This reduced storage may shorten nitrate residence time and slightly increase the potential for leaching, especially during high-input or high-precipitation events. However, conservation tillage improved AWC at CU2 relative to conventional tillage, and native soils (e.g., N2 with AWC of 11.5%) consistently held more water, reinforcing the role of management and disturbance in regulating water and solute movement. Collectively, these characteristics are expected to reduce nitrate leaching risk under typical near-saturated conditions by promoting matrix flow and increasing the residence time of water and nitrate in biologically active zones. However, under heavy or prolonged rainfall, the potential for preferential flow through macropores could still elevate leaching risk, particularly where structural continuity exists through the clay layer.

The Colorado Piedmont is an arid environment where evapotranspiration exceeds precipitation, resulting in minimal leaching (unless irrigated), limited chemical weathering, and the precipitation of certain elements as carbonates in lower soil horizons. Accumulation of $CaCO_3$ occurs under conditions typical of dry environments, high pH, and high evapotranspiration (Kelly et al., 2008). Previous research has shown that nitrate can weakly adsorb onto calcium carbonate in calcareous soils, especially when the $CaCO_3$ has a high surface area. This adsorption can temporarily reduce nitrate leaching but is easily reversed by competing anions like sulfate. As a result, while calcium carbonate may slow nitrate movement, it does not provide long-term retention under field conditions with elements higher on the lyotropic series, such as sulfate, readily displacing nitrate from adsorption sites (Singh & Sekhon 1978). That said, secondary calcium carbonate accumulation influences nitrate leaching potential circumstantially.

The calcium carbonate levels observed in both semi-arid systems suggest that while $CaCO_3$ may not strongly retain nitrate, it could delay leaching, particularly in deeper horizons where concentrations increase. In CU1, the accumulation of up to 600 g cm^2 $CaCO_3$ at depth, along with massive structure, likely contributes to restricted water movement and longer nitrate residence times. At CU2, the overall 20% higher carbonate content and zone of maximum accumulation (50-125cm) increase of $CaCO_3$ with depth may reflect ongoing carbonate translocation and points to increased potential for lateral flow. Deeper in the profile, zones where both carbonate and bulk density sharply increase likely impede infiltration and reduce the retention of nitrate.

Understanding nitrate leaching potential in these systems requires a field-scale, site-specific interpretation of how measured soil properties interact to influence water movement and solute transport. Soil texture and organic matter, though relatively stable in the short term, are foundational indicators of microporosity and available water capacity (AWC), while soil structure, more sensitive to land use and disturbance, modulates macroporosity and thus plays a critical role in fluid flow. At CU1, the combination of fine-textured soils, organic matter-rich mollic epipedon, subangular blocky structure, and argillic horizon creates a synergistic effect that promotes high water retention and matrix-dominated flow. However, the plow pan alters surface hydrology by promoting runoff under unsaturated conditions. Deeper in the profile, massive structure and increased carbonate likely promote lateral flow. This integrated system increases nitrate residence time within the root zone and reduces leaching risk under typical field conditions. At CU2, granular surface structure enhances infiltration into the clay-rich upper profile, but lower AWC and a thick compacted plow pan constrain water storage and vertical percolation, potentially increasing leaching risk during high-intensity water inputs. Conservation tillage improves water retention here, and native soils consistently exhibit higher AWC, indicating management-sensitive control of nitrate mobility. Zones of secondary $CaCO_3$ accumulation and increased bulk density further moderate leaching by lowering leaching potential, slowing infiltration, and favoring lateral flow of water. Collectively, the most informative predictors of leaching potential in these systems are expected to be: (1) the vertical distribution of structure and its influence on macroporosity; (2) the depth and integrity of restrictive features (e.g., plow pans, argillic horizons, carbonate plugging); (3) texture, organic matter content, and associated water retention; and (4) the presence and concentration of secondary calcium carbonates. These factors interact in complex ways, underscoring the need to evaluate leaching risk as an emergent property of the entire soil system rather than any single parameter in isolation.

CHAPTER 3: PEDOGENIC CONTROLS AND STATISTICAL ANALYSIS

1. INTRODUCTION

Nitrate leaching has been a subject of active research since the 1960s, evolving from basic field measurements to sophisticated modeling frameworks that integrate hydrological, chemical, and biological processes (Liu et al., 2025). As concerns over climate change, groundwater contamination, and agricultural sustainability intensify, the ability to accurately quantify and predict nitrogen leaching across spatial and temporal scales has become increasingly important. Recent advances in modeling, such as NLEAP (Shaffer et al., 1991), and other process-based or empirical approaches, have enabled researchers to simulate nitrate transport with greater precision, offering valuable insights into nutrient dynamics under varying land-use and climatic conditions. Such advancements enhance our ability not only to quantify nitrate leaching but also to anticipate its long-term impacts on ecosystem function and water resource quality, thereby informing sustainable land management strategies.

Despite the extensive body of literature on nitrate leaching, there remains a notable gap in field-scale pedological analysis within cultivated soils of Colorado (Shaffer et al., 2004; Wey et al., 2022; Ceplecha et al., 2004). Specifically, limited research has employed advanced statistical modeling to identify site-specific factors controlling leaching potential. While tools like the Colorado Nitrogen Leaching Index offer valuable regional-scale insights, their applicability to specific site-level management decisions may be limited by the inherent complexity and variability of local conditions, an important consideration shared by many broad-scale assessment tools. Previous research has established foundational knowledge on groundwater vulnerability and nutrient management, yet additional work is needed to integrate soil-specific properties within predictive modeling frameworks (Ceplecha et al., 2004; Sharkoff et al., 2012).

2. SECTION OBJECTIVES AND METHODOLOGY

2.1 MODELING APPROACH BASED ON RESEARCH OBJECTIVES

To address this gap, this study integrates field-collected soil property data from the South Platte and Arkansas River Basins with historical deep nitrate concentration data from the Colorado State University Agricultural Water Quality Program (AWQP). The research employs a multi-step analytical framework:

1. Principal Component Analysis (PCA): Used to reduce dimensionality and identify key soil properties driving variability across sites (Pearson 1901; Hotelling 1933).
2. Linear Mixed-Effects Modeling (lmer): Applied to evaluate the influence of identified soil properties on nitrate concentrations, accounting for repeated measures and nested sampling structures (Galeki et al., 2013).

3. Sensitivity Analysis: Conducted to assess how variations in key input variables affect nitrate leaching potential, thereby identifying the most influential controls.

This approach enables a comprehensive evaluation of nitrate leaching dynamics by:

- Isolating dominant soil-based controls on nitrate variability.
- Predicting nitrate concentrations using statistically significant soil properties.
- Quantifying the sensitivity of leaching potential to changes in these controls.

By integrating pedological data with advanced statistical techniques, this research contributes to a more nuanced understanding of nitrate leaching in Colorado's cultivated soils. It fills a critical gap in the literature by offering site-specific insights that can inform targeted nutrient management and groundwater protection strategies.

The objective of this chapter is to identify and quantify the soil and environmental parameters that most strongly influence nitrate leaching potential. To accomplish this, PCA is employed to determine the key driving variability within the dataset. These drivers are then incorporated into predictive modeling to evaluate their relationship with nitrate concentrations and identify the dominant factors controlling their distribution. Finally, scenario-based analyses are used to quantify how changes in each parameter affect nitrate concentrations, thereby establishing which variables are most likely to govern nitrate leaching potential. The primary question addressed in this chapter is: *What are the properties in these systems driving leaching potential?* To address this question, a combination of multivariate statistical analysis, predictive modeling, and scenario testing is applied, providing a framework for linking soil properties to nitrate dynamics in a quantifiable and systematic way.

2.2 PEDOGENIC HORIZON NITRATE NORMALIZATION

To align historical nitrate measurements with pedogenic horizons, we developed a normalization approach that redistributed fixed-depth AWQP nitrate concentrations into horizon-based values. Since AWQP samples were collected at fixed intervals (0–8 in, 8–24 in, 24–36 in, etc.) that do not correspond to natural soil horizons, we applied a weighted averaging method to partition each fixed-depth nitrate concentration into the appropriate horizons. This was done by proportionally assigning portions of the measured concentration to overlapping depths based on the thickness of each horizon. For example, if a horizon spanned across two sampling intervals, the nitrate concentration was weighted by the fraction of the horizon within each interval and then summed to produce a horizon-specific value. This method ensured that nitrate concentrations were systematically and transparently aligned with soil development patterns, enabling meaningful comparison of nitrate dynamics across pedogenic horizons.

3. RESULTS

3.1 ISOLATING SOIL PROPERTY CONTROLS ON NITRATE VARIBILITY

PCA is employed to reduce the dimensionality of the dataset and identify the parameters that account for the greatest variability across sites. This approach is particularly well-suited for soil-related datasets, which often contain highly interrelated variables (e.g., texture, organic matter, and bulk density) that can obscure the primary drivers of nitrate dynamics.

PCA is able to identify relationships among correlated soil properties and reduce them into uncorrelated principal components. This approach highlights the dominant patterns of variability controlling nitrate behavior across sites. All variables were standardized to account for differing measurement scales. PCA reveals how soil property groupings relate to nitrate retention.

By transforming the original correlated variables into a smaller set of uncorrelated principal components, PCA allows for a clearer understanding of the underlying structure of the data. This technique was used as a guide to inform covariate selection for the mixed model linear regression.

PCA was run as a separate test for each watershed basin. The suite of variables included in the PCA consists of: depth upper, depth lower, pH, electrical conductivity (EC), total carbon, total nitrogen, carbon-to-nitrogen ratio, total calcium carbonate, total inorganic carbon, total organic carbon, total organic matter, bulk density, and the percentages of sand, silt, and clay.

Field capacity, wilting point, and available water capacity (AWC) are excluded from the analysis because these data were only available for the CT1 North and ST2 South locations at each site, leaving empty cells for the remaining locations. Because PCA requires complete data for each variable, including these parameters would have introduced missing values that could not be accommodated without imputation, which was not appropriate for this analysis.

PCA is conducted to reduce the dimensionality of the soil dataset and identify the main sources of variation among the variables. The scree plots (Figure 3.1, 3.2) show the proportion of variance explained by each principal component (PC). At CU1, PC 1 - 4 explains 89.7%. At CU2 PC 1-4 explain 94% of the total variance, indicating that most variability in the soil dataset is captured by these components.

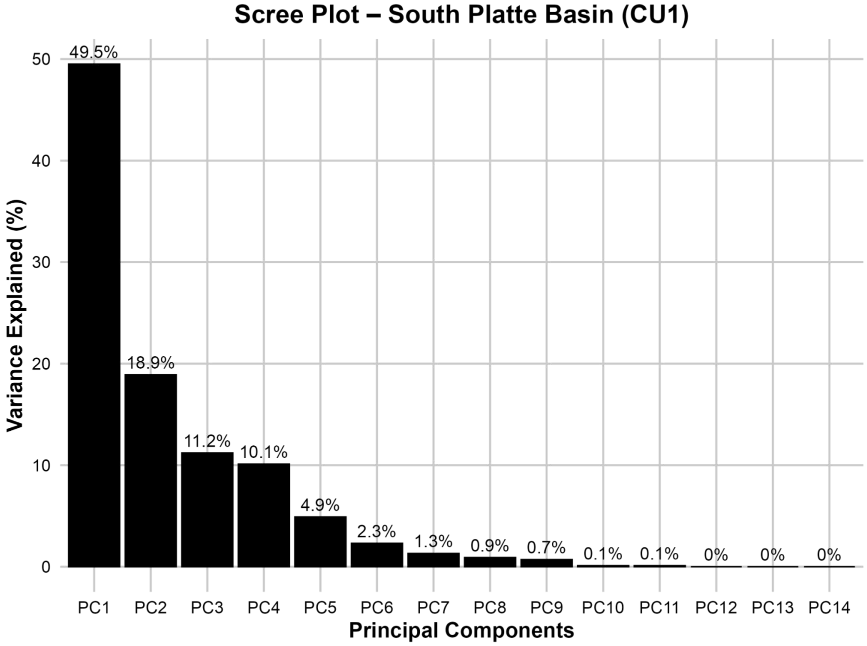


Figure 3.1. Scree plot for CU1 of principal components for soil variables. The plot shows the proportion of variance explained by each principal component (PC).

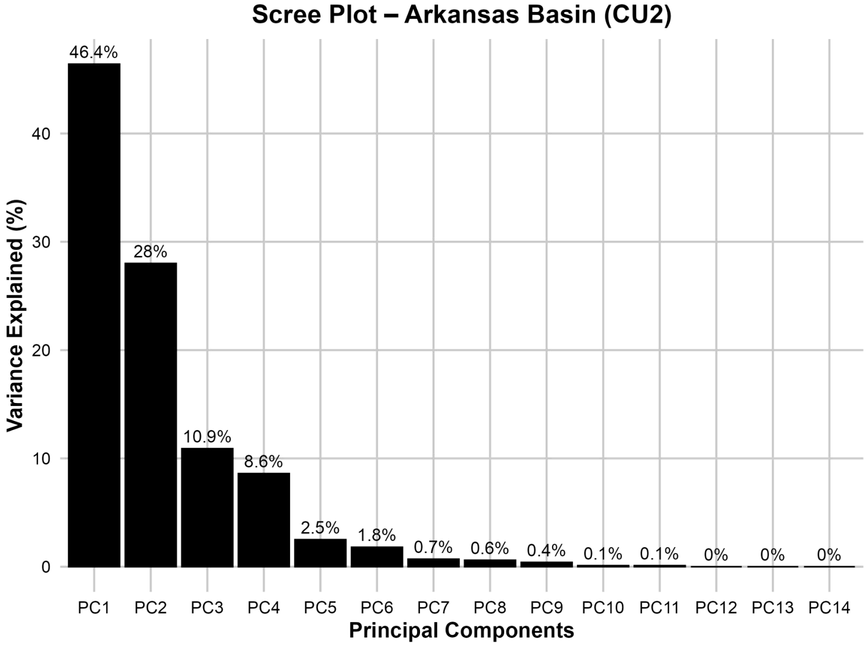


Figure 3.2. Scree plot for CU2 of principal components for soil variables. The plot shows the proportion of variance explained by each principal component (PC).

In PCA, a loading represents how strongly each original variable contributes to a principal component. Large absolute loadings indicate variables that define the component the most. Positive loadings mean the variable increases with the component, while negative loadings mean it moves in the opposite direction. By examining loadings, you can understand which variables drive each principal component.

The loading plots for the first three principal components (PC1–3) illustrate key contributors of variation among soil properties at CU1 (Figure 3.3). PC1 is characterized by strong loadings for total carbon, inorganic carbon, $CaCO_3$, total nitrogen, clay, and horizon thickness. PC2 shows high loadings for bulk density, sand, and organic matter, reflecting variation in surface structure and organic accumulation across horizons. PC3 is dominated by electrical conductivity, sand, pH, and bulk density, indicating a secondary gradient related to texture and soluble salts. Collectively, PC1–3 captures the dominant physical and chemical contrasts within the CU1 soil profile.

The loading plots for CU2 (Figure 3.4) display similar but distinct gradients in soil properties. PC1 shows strong loadings for organic matter, organic carbon, total nitrogen, and C:N ratio, contrasting with depth and bulk density, representing a gradient between surface organic enrichment and deeper, compacted horizons. PC2 is driven by clay, horizon thickness, and total and inorganic carbon. PC3 is dominated by sand, bulk density, and depth, capturing the influence of coarse texture and compaction on soil variability. Together, these components describe the dominant gradients in organic composition, texture, and carbonate distribution within the Arkansas Basin profile.

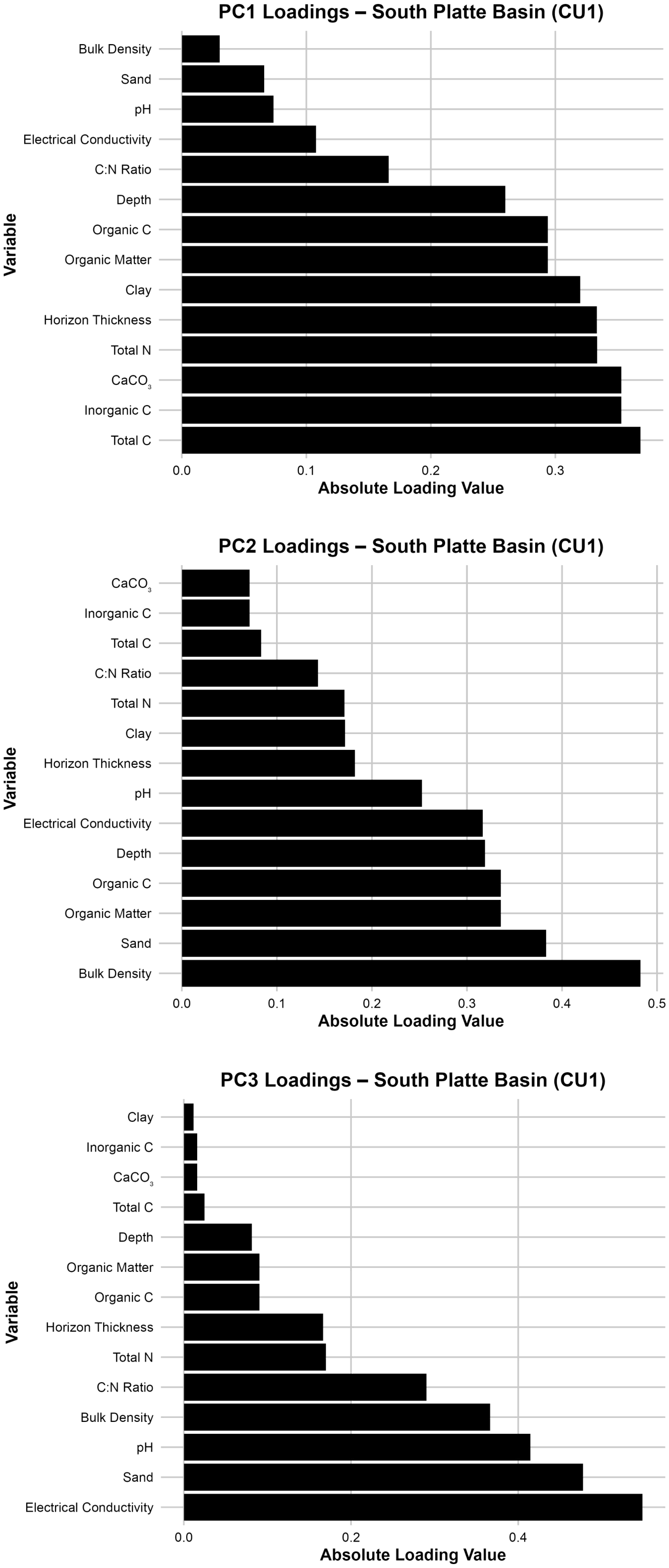
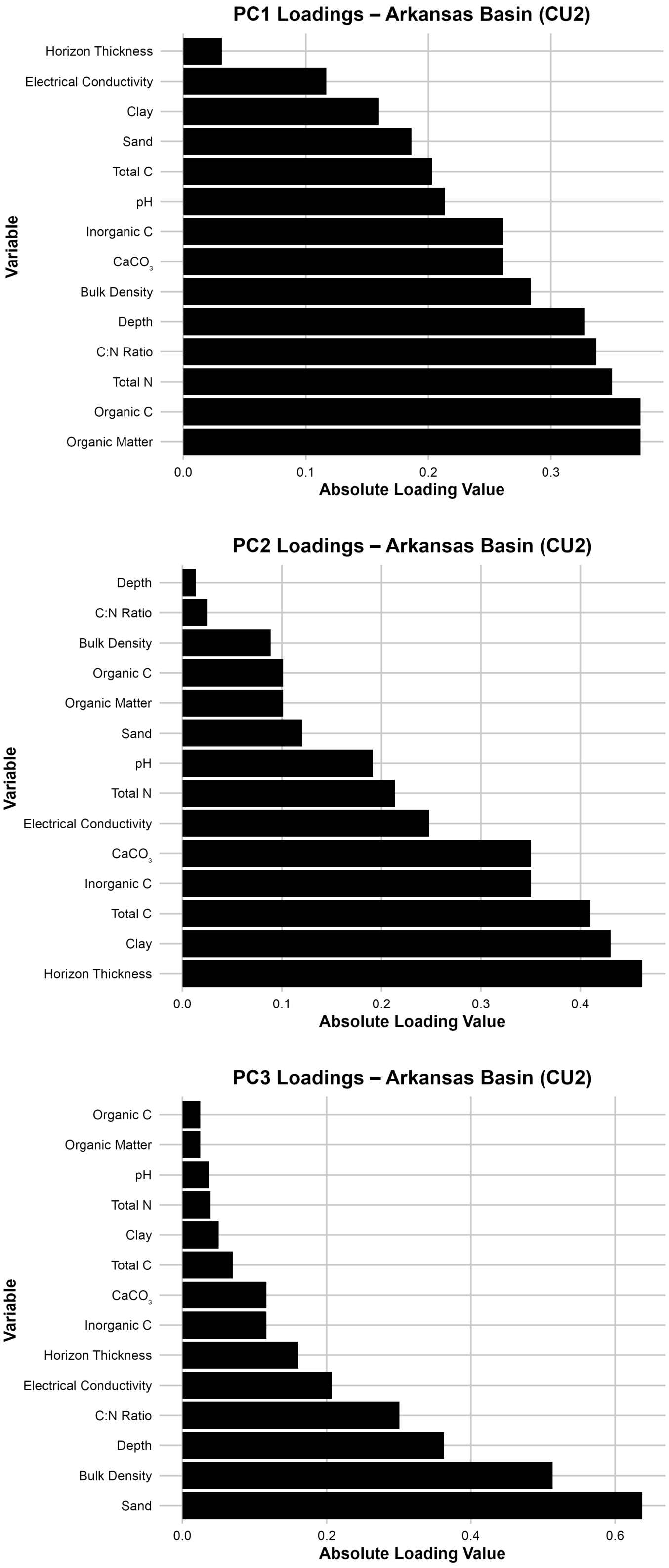


Figure 3.3. CU1 loadings plot for Principal Component 1-3 (PC1-3). The plots display the contribution of each soil variable to PC1-3.



PC1 Loadings – Arkansas Basin (CU2)

PC2 Loadings – Arkansas Basin (CU2)

PC3 Loadings – Arkansas Basin (CU2)

Figure 3.4. CU2 loadings plot for Principal Component 1-3 (PC1-3). The plots display the contribution of each soil variable to PC1-3.

3.2 LINEAR MIXED-EFFECTS MODELING AND NITRATE PREDICTION STATISTICS

To ensure a parsimonious and interpretable model structure, a combination of statistical diagnostics (Figure 3.3, 3.4) and soil system theory is used to guide parameter selection. A separate model was created for each watershed basin to establish differences in controlling indicators significantly associated with nitrate concentration. We use PCA results to choose model parameters, and conduct Variance Inflation Factor (VIF) assessments to identify collinear or redundant variables (Zurr et al., 2010). VIFs are calculated for all independent variables to address multicollinearity, which can inflate the variance of regression coefficients caused by strong correlations among predictors. Following the protocol recommended by Zuur et al. (2010), covariates with the highest VIFs are sequentially removed and recalculated until all remaining variables have VIF values below the threshold of 10, as suggested by Montgomery and Peck (1992).

From the resulting pool of statistically acceptable predictors, the final variables are selected based on their theoretical relevance to soil hydrology and nutrient transport. Fixed effects are carefully chosen to reflect meaningful ecological interpretations, while random effects are incorporated to control for unobserved variability associated with spatial and temporal factors. In particular, Year and Strip ID are included as random effects to account for repeated measurements and unobserved spatial autocorrelation, respectively. This hierarchical structure allows the model to accommodate nested and repeated data while maintaining the interpretability of the fixed effects.

Sampling years at CU1 2011, 2013, 2014, 2017, and 2023 were associated with irregular sampling conditions and methodological inconsistencies, as indicated by outliers and variability patterns observed in boxplots (Figure 3.5).

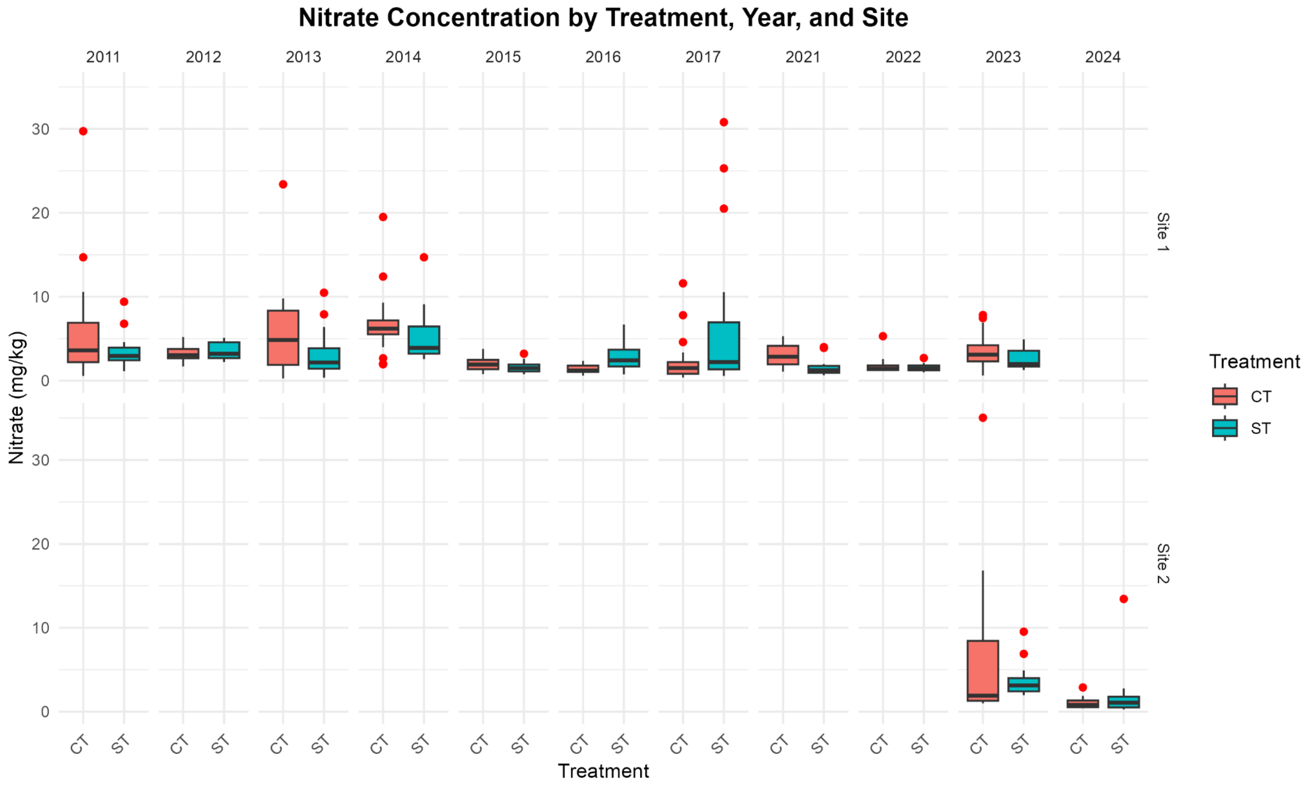


Figure 3.5. Boxplots of soil nitrate concentrations by treatment (CT = conventional till, ST = strip till) across sampling years. Each panel represents a different sampling year, with red points indicating outliers beyond 1.5× the interquartile range. Years 2011, 2013, 2014, 2017, and 2023 display elevated variability and outlier frequency compared to other years.

Linear mixed-effects modeling is conducted in R (R Core Team 2025) using the *lmer* function from the package lme4 (Bates et al., 2015). Backward stepwise regression is applied using the *step* function to select the best-fitting model based on Akaike's

Information Criterion (AIC), a metric that estimates the relative quality of statistical models by balancing goodness-of-fit with model complexity.

Analysis of variance (Anova Type III) is then used to assess the significance of fixed effects in predicting soil nitrate concentration across all depths, sites, treatments, and locations.

Fixed effects included in both final models contain tillage treatment, depth of the lower horizon break (cm), organic matter, bulk density, total $CaCO_3$ content, total nitrogen content, and total clay equivalence (Table 3.5).

Available water capacity (AWC), field capacity, and wilting point measurements were only collected for select sites, treatments, and field locations, rather than consistently across the full dataset. Because these variables contained many missing values, their inclusion would have triggered listwise deletion and substantially reduced the number of observations available for analysis. To preserve statistical power and maintain a representative model, these covariates were excluded from the final set of predictors.

Model accuracy is assessed using the Pearson correlation coefficient (r), associated p-values, and root mean square error (RMSE) between observed and predicted nitrate concentrations. Final variable selection for each model was based on statistical significance, incremental gains in predictive performance, and diagnostic evidence of adequate fit.

South Platte Basin – Type III ANOVA Results

Variable	Chisq	Df	Pr(>Chisq)
(Intercept)	1,358.394	1	0.000
Bulk Density	1.626	1	0.202
$CaCO_3$	8.991	1	0.003
Clay	9.820	1	0.002
Tillage Treatment	2.942	1	0.086
Organic Matter	3.245	1	0.072
Total Nitrogen	14.940	1	0.000

South Platte Basin – Fit Statistics

Statistic	Value
RMSE	0.011
Marginal R^2	0.157
Conditional R^2	0.410

Table 3.5. South Platte Basin (CU1) Type III ANOVA and model fit statistics for the mixed-effects model predicting log-transformed nitrate concentration (logNO_3^-) from key soil and management variables.

Arkansas Basin – Type III ANOVA Results

Variable	Chisq	Df	Pr(>Chisq)
(Intercept)	46.527	1	0.000
Bulk Density	0.000	1	0.990
$CaCO_3$	0.013	1	0.910
Clay	0.217	1	0.641
Tillage Treatment	0.125	1	0.724
Organic Matter	1.086	1	0.297
Total Nitrogen	2.690	1	0.101

Arkansas Basin – Fit Statistics

Statistic	Value
RMSE	0.016
Marginal R^2	0.120
Conditional R^2	0.727

Table 3.6. Arkansas Basin (CU2) Type III ANOVA and model fit statistics for the mixed-effects model predicting log-transformed nitrate concentration (logNO_3^-) from key soil and management variables.

The South Platte Basin (CU1), Type III ANOVA results indicate that total $CaCO_3$ (g/cm^3), total clay (g/cm^3), and total nitrogen (g/cm^3) have the strongest statistical influence on log-transformed nitrate concentration (logNO_3^-) among the predictors assessed. This finding does not imply that the other parameters have no effect on nitrate concentration; rather, it suggests that total $CaCO_3$, clay, and total N may be a more prominent driver of water movement and thus nitrate dynamics within the soil profile in this system.

The Arkansas Basin (CU2) Type III ANOVA results indicate that no soil properties demonstrated a strong statistical influence on log-transformed nitrate concentration (logNO_3^-). This finding does not imply that these parameters have no effect on nitrate concentration; rather, it suggests that within-site variability and hydrologic or management factors may exert greater influence on nitrate dynamics than the measured soil properties alone. The relatively higher conditional R^2 compared to the marginal R^2 further supports this interpretation, indicating that random effects such as strip- and year-level variation explain a substantial portion of the overall variability in nitrate concentrations.

The contrasting model performance between the South Platte (CU1) and Arkansas (CU2) basins is likely influenced in part by differences in dataset size and temporal representation. The CU1 model was trained on approximately ten years of data (~400 observations), encompassing a wide range of conditions. This broader temporal and observational base provides stronger statistical power and a more stable representation of long-term relationships among soil properties and nitrate concentration. In contrast, the CU2 model was developed from only two years of data

(~40 observations), which limits its ability to capture interannual variability and reduces model robustness. Consequently, weaker statistical relationships at CU2 may reflect both reduced sample size and narrower environmental variability, rather than the absence of true pedologic or management effects on nitrate dynamics.

These findings suggest three key conclusions:

1) The absence of significant linkages at the AVRC (CU2) point to the importance of long - term datasets for capturing pedogenic and hydrology relationships. It may also suggest that the dominant pedogenic processes expressed at this site exert limited control over regulating water movement.

2) At ARDEC (CU1), carbonate content and clay emerged as significant indicators for water movement in this system. These variables play a particularly important role in explaining variation in nitrate concentrations within the soil profile.

3) Total N was also a key predictor, reflecting its close association with nitrate production and the nitrogen pool.

3.3 THRESHOLD ANALYSIS STATISTICS

To further evaluate how pedogenic properties regulate nitrate behavior, two supplementary analyses were conducted.

First, marginal effects modeling was used to visualize the continuous responses of predicted nitrate concentrations to key soil properties using the mixed-effects models created for each basin. The linear mixed models describe the overall direction and magnitude of relationships between soil variables and log-transformed nitrate concentrations while accounting for treatment and random effects. These plots illustrate how nitrate concentrations change along gradients of $CaCO_3$, total nitrogen, and clay content across basins and management treatments (Figure 3.6).

Second, a threshold analysis (using segmented regression) was performed to test whether distinct breakpoints exist in these relationships, indicating soil property levels at which nitrate behavior changes direction or intensity. The segmented regressions isolate potential nonlinear thresholds where shifts in soil conditions, such as carbonate accumulation or increasing clay content, begin to alter nitrate dynamics. Together, these analyses provide both continuous and threshold-based perspectives on how soil properties influence nitrate dynamics within CU1 and C2 agricultural soils (Figure 3.7).

These complementary approaches highlight that while average trends remain modest, distinct pedogenic thresholds mark transitions between leaching-dominated and nitrate-retentive zones within each basin.

These modeling approaches address objectives 1 and 2 of this study by quantifying the direction of effect each key indicator (total $CaCO_3$, total nitrogen, and clay content) plays in influencing predicted nitrate concentrations across basins and testing whether tillage treatment level differences are important in regulating nitrate mobility.

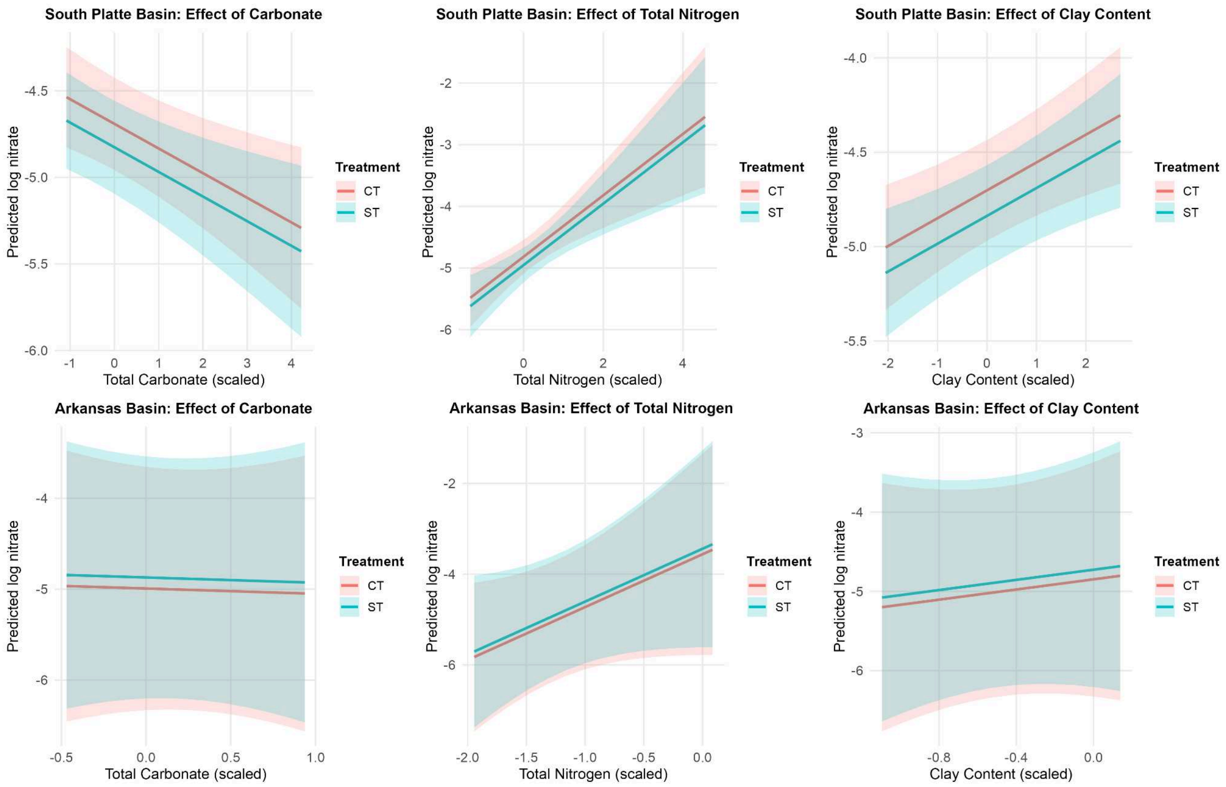


Figure 3.6. Predicted effects of total $CaCO_3$, total nitrogen, and clay content on log-transformed nitrate concentrations across the South Platte (top row) and Arkansas (bottom row) basins. Model-based marginal effects were derived from linear mixed-effects models comparing conventional (CT) and strip-tillage (ST) management. Shaded ribbons represent 95% confidence intervals around the predicted means.

In the South Platte Basin (CU1), the direction of influence varies by covariate. Total nitrogen and clay content are linked to positive relationships with predicted nitrate, whereas carbonate exhibits a negative relationship.

In the Arkansas Basin (CU2), modeled effects were weaker and more uniform across soil properties. Slight positive slopes for total nitrogen and clay were observed, but wide confidence intervals indicated limited predictive strength consistent with ANOVA results. The near-neutral relationship between $CaCO_3$ and nitrate suggests minimal carbonate influence on nitrate dynamics.

Predicted relationships were consistent between treatments across all sites. While both CT and ST showed similar directional responses to covariates, CT generally resulted in slightly higher concentrations at CU1, while ST exhibited higher concentrations than CT at CU2 for each covariate.

Covariate threshold points for CU1 and CU2 are displayed in Figure 3.7. In the South Platte Basin, carbonate, total nitrogen, and clay content each displayed mild inflection points, indicating nonlinear but relatively gradual responses. Because soil variables were standardized prior to analysis, threshold values are expressed in scaled units representing standard deviations from the mean. To improve interpretability, these thresholds were converted back to original units using each variable's mean and standard deviation.

The South Platte carbonate threshold of 2.52 (scaled) corresponds to approximately 1534 g cm^3, or about 460 g cm^3 above the mean value of 1073 g cm^3. This indicates that nitrate retention occurs only under exceptionally carbonate-enriched conditions, roughly 2.5 standard deviations above the basin mean.

The total nitrogen threshold of –0.25 (scaled) corresponds to approximately 16.3 g cm^3, about 0.7 g cm^3 below the mean. This suggests that nitrate availability begins to increase once total nitrogen exceeds its lower-than-average value, indicating that even small increases in soil nitrogen pool size support greater nitrate accumulation through enhanced mineralization.

The clay threshold of –0.02 (scaled) corresponds to approximately 7738 g cm^3, effectively equal to the mean clay content. This minimal deviation indicates that nitrate rises drastically even under typical clay conditions, suggesting that fine textures limit infiltration and enhance nitrate retention in near-surface or subsoil horizons.

While the segmented and mixed-effects models identified several apparent thresholds and directional trends, model diagnostics and Type III ANOVA results indicated no statistically significant soil predictors of nitrate concentration. Therefore, these findings should be interpreted cautiously as exploratory patterns rather than definitive relationships.

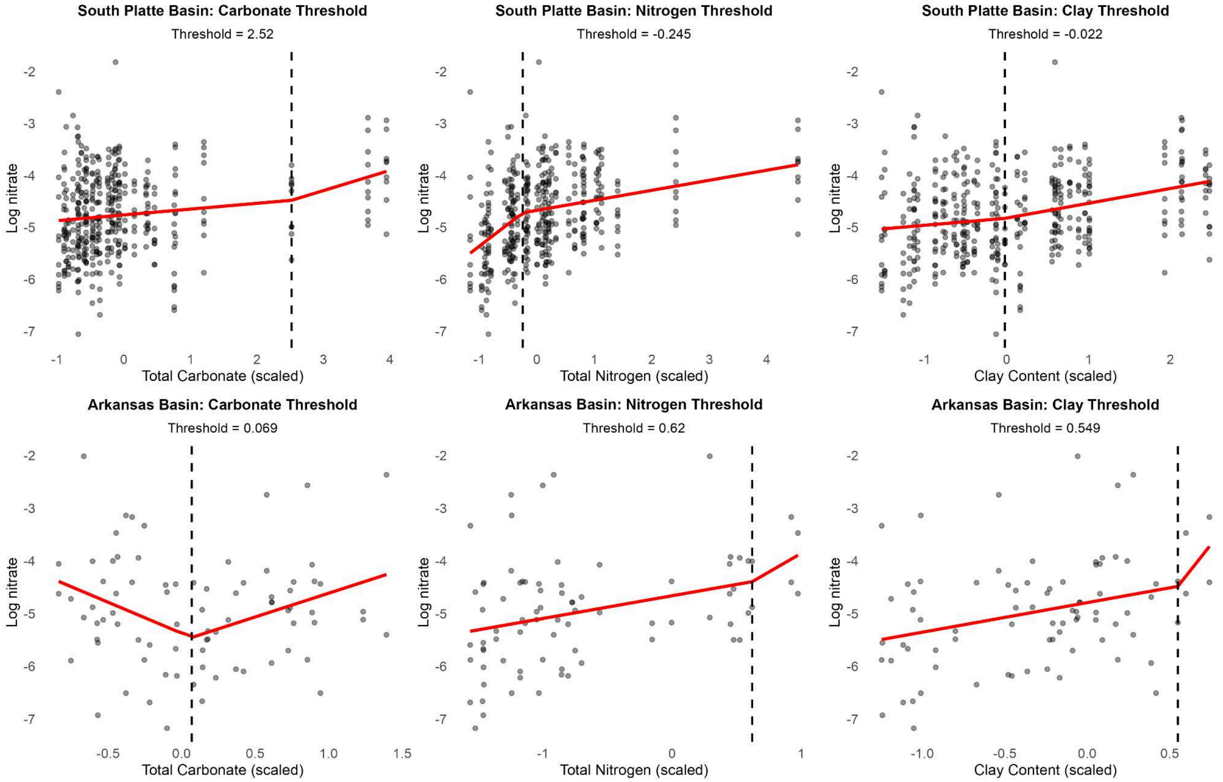


Figure 3.7. Segmented regression models showing threshold relationships between total $CaCO_3$, total nitrogen, and clay content and log-transformed nitrate concentrations across the South Platte (top row) and Arkansas (bottom row) basins. The red lines represent fitted segmented regressions, and dashed black lines indicate estimated breakpoints (thresholds). Shaded data points represent observed log nitrate values, illustrating where changes in slope signify shifts in nitrate response to soil property levels.

4. DISCUSSION

Semi-arid and irrigated agricultural systems along the Colorado Piedmont are particularly vulnerable to water quality degradation from nitrate leaching due to intensive fertilizer use, furrow irrigation, and inherent soil properties (Bauder et al., 2012). These conditions make the region an important case for evaluating how pedogenic development and management practices interact to regulate nitrate transport. In this chapter, we applied a multi-step analytical framework - Principal Component Analysis (PCA), linear mixed-effects modeling (LMM), and threshold analysis - to identify and quantify the soil properties that most strongly influence nitrate leaching potential. Together, these analyses revealed the dominant drivers of nitrate concentrations within the data and clarified how subsurface processes, soil structure, and carbonate accumulations constrain or facilitate nitrate mobility.

At CU1, PCA showed variation was driven by nutrient pools, carbonate, clay, soil depth, and bulk density, while at CU2, contrasts between nutrient pools, bulk density, texture (clay and sand), horizon thickness, and carbonate were observed. Together, these gradients reflect the interplay of pedogenic development, texture, and organic matter that underlie differences in nitrate behavior across basins.

In the South Platte Basin, LMM results highlighted total calcium carbonate ($CaCO_3$), total clay, and total Nitrogen as the most statistically significant predictors of nitrate concentrations. Calcium carbonate also showed a negative relationship with nitrate. While carbonate-rich horizons have often been predicted to adsorb and retain nitrate (Singh & Sekhon, 1978), the patterns observed here suggest different mechanisms. One possible explanation is that elevated $CaCO_3$ content may alter pore structure by dispersing clays and restricting vertical drainage (Pal et al., 2000), and/or create alkaline conditions that enhance microbial denitrification, thereby reducing measurable nitrate concentrations. These hydropedological and biogeochemical interactions highlight the complex role of carbonate accumulations in modulating leaching pathways.

The contrasting model performance between the South Platte (CU1) and Arkansas (CU2) basins likely reflects both differences in dataset size and temporal representation, and the possibility that within-site variability, driven by hydrologic or management factors, exerts greater control on nitrate dynamics than the measured soil properties alone.

Threshold analyses reinforced these findings by highlighting the trends in predicted nitrate to changes in key indicators within the South Platte Basin. Clay generally exhibited a negative relationship with predicted nitrate, while clay and total N corresponded with a positive relationship. Carbonate accumulation above the mean was the threshold point that resulted in hydrologic plugging, therefore locking in nitrate within the profile. Clay distribution and total nitrogen content near the site mean represented the threshold point at which nitrate persistence began to increase noticeably, indicating that even moderate changes in these properties can shift the balance between nitrate retention and leaching within the profile.

These results are broadly consistent with prior work in Colorado and other semi-arid regions. Nitrogen availability has long been recognized as a primary driver of nitrate production and accumulation under irrigated agriculture (Rupert, 2008; Bauder et al., 2011). Similarly, clay distribution has been identified as a key constraint on infiltration and preferential flow (Lin, 2012; Strock et al., 2022). The finding that $CaCO_3$ generally reduces nitrate concentrations is more novel, yet aligns with research linking carbonate-rich horizons to reduced permeability and potential denitrification hotspots (Pal et al., 2000).

Although management influenced soil structure, bulk density, AWC, C:N, and organic matter distribution, their effects were smaller than those of inherent pedogenic and hydrologic properties. Conservation-oriented tillage may help maintain pore continuity and organic matter inputs, but subsurface horizons, inherent fine soil texture, total nitrogen, and carbonate accumulated layers exert stronger control on nitrate mobility in these systems. This suggests that water quality protection strategies must combine nutrient management (e.g., aligning fertilizer timing and rates with crop demand) with field-scale evaluations of soil horizons and restrictive features. By linking management interventions to site-specific pedogenic context, producers can better mitigate nitrate loading risks in semi-arid irrigated landscapes (Bauder et al., 2018; Huang et al., 2024).

CHAPTER 4: CONCLUSIONS

This study examined how pedogenic soil properties influence nitrate leaching potential in semi-arid cultivated soils of Colorado. The work focused on linking profile-scale soil properties to nitrate variability under furrow irrigated conservation and conventional tillage systems. Pedon characterization, multivariate statistical modeling, and threshold analysis were used to identify the properties most strongly associated with nitrate concentrations and to evaluate their predictive capacity as volumetric amounts change. The central research question asked which soil system properties most strongly control nitrate leaching in irrigated Colorado soils, and how these controls are modified by tillage practices.

In comparing the sites, diverse pedogenic settings provide the foundation on which water movement is regulated. Fine-textured parent material dictates fine-textured soils at CU1, contrasting with more coarse-textured soils derived from coarse parent material at CU2. Textural characteristics imparted to the soils by the contrasting parent materials control the quantities of materials produced and retained in the soil, but also the degree of processes like translocation of clay minerals within the soil, thereby influencing the hydrology, AWC, and leaching risk potential.

Key relationships are best characterized by combining the pedologic characteristics within vertical zones among the soil profiles at each site with statistical inferences from the modeling results. Vertical zones of high clay distribution near the middle of the soil profile act as zones of slow infiltration, reduced downward movement, and high nitrate retention. This is supported by the positive relationship between clay and predicted nitrate.

Increase of calcium carbonate content with profile depth acts as zones of slow infiltration, favoring lateral flow, thereby reducing water retention and consequently nitrate retention. Thus, lower in the soil horizon, we would expect to see promotion of lateral flow redirecting and reducing downward leaching. This is supported by the negative relationship between carbonate and predicted nitrate. Another meaningful comparison was in this pedogenic setting, nitrate persistence was notably increased 2.5 standard deviations above the mean carbonate, highlighting that zones where high concentrations of carbonates occur likely point to pore space plugging at this threshold, locking in nitrate and reducing leaching potential.

Despite these resistive factors, the positive relationship between total nitrogen and nitrate concentrations underscores that fertilizer loading remains as important as any pedogenic property in determining water quality risk. This is supported by the positive relationship between total N and nitrate. Additionally, the potential for increased nitrate availability to be leached occurred around the mean value for total N at this site, indicating the threshold for total N at which leaching can occur more readily. Soils at CU1 exhibit characteristics that favor net mineralization, and management practices appear to lower C:N ratios, promoting mineralization pathways and the release of available nitrogen. This increases the soil's availability for nitrogen leaching, acting against the resistive clay and carbonate features.

Native soils across basins showed management influenced soil structure, increased bulk density, reduced AWC, and C:N, favoring mineralization, and reducing organic matter content. Though it was not identified that tillage management specifically served as a proxy for water flow, it established that furrow irrigation systems reduce AWC and organic matter while also pushing the system towards net mineralization, thereby increasing the potential for leaching to occur.

Taken together, the statistical findings and pedologic context converge on the conclusion that nitrate leaching potential in these semi-arid systems is governed less by surface management in the short term and more by subsurface horizons and pedogenic features that dictate how water and solutes move through the profile. These dynamics emphasize that nitrate leaching potential is an emergent property of the whole soil system, integrating nutrient pools with hydrologic architecture.

These findings suggest effective nitrate management requires matching fertilizer inputs to crop demand while recognizing that subsurface horizons, carbonate layers, and clay exert stronger control on leaching than surface tillage. Conservation practices can enhance organic matter and water retention, but site-specific soil architecture ultimately dictates nitrate fate. This highlights the importance of field-scale data-driven approaches to the issue of water quality. Conceptually, this work reinforces a soil-system perspective: fertilizer management sets the magnitude of nitrate at risk, but pedogenic controls determine its fate.

The lack of statistically significant linkages between soil properties and nitrate concentrations in the Arkansas Basin (CU2) likely reflects a combination of both data limitations and site-specific soil behavior. While the South Platte Basin (CU1) model benefited from a decade of nitrate observations, the Arkansas Basin dataset spanned only two years, reducing statistical power and the model's ability to capture interannual variability in hydrologic and management conditions. Because nitrate dynamics are temporally sensitive to fertilizer inputs, irrigation frequency, and seasonal weather patterns, short-term datasets tend to capture transient responses rather than longer-term pedologic trends.

At the same time, the absence of strong relationships may also suggest that, in this particular pedogenic setting, the dominant soil-forming processes do not exert the same degree of hydrologic control as observed in more developed systems like CU1. Younger or more weakly expressed horizons, coupled with coarser textures, may limit the extent to which pedogenic architecture governs water movement and solute transport. In such systems, management intensity, irrigation timing, and annual water balance may temporarily outweigh the slower, cumulative effects of pedogenic regulation.

Taken together, these findings highlight two key implications: (1) long-term, multi-year datasets are essential for statistically resolving the influence of slowly acting soil-forming processes on nitrate dynamics, and (2) pedogenic control over nitrate leaching may be weaker or more indirect in less-developed or coarser-textured systems, where short-term hydrologic variability and management practices dominate nitrate transport behavior.

The main limitation of this study is its reliance on observational data collected across heterogeneous sites and years, which may obscure treatment effects under specific climatic or management conditions. Available water capacity, while mechanistically important, could not be fully integrated due to missing values. Despite these constraints, the dataset is unique in combining 10 years(CU1) and 2 years (CU2) of deep nitrate profiles with detailed pedological characterization, and the statistical framework applied here is well-suited to nested and repeated measures. Future research should examine long-term hydropedological changes in relation to nitrate concentrations across genetic boundaries, with particular attention to parent materials, carbonate, microbial interactions, denitrification processes, and preferential flow pathways under varying tillage and irrigation regimes.

From a management perspective, these findings underscore the importance of aligning irrigation, nutrient management, and soil monitoring with the inherent pedogenic framework of each system. Where feasible, transitioning from furrow to more precise irrigation methods such as drip or sprinkler can reduce deep percolation and nitrate loss. The influence of parent material on clay content is also critical, as finer-textured alluvial soils tend to promote greater clay illuviation, an effect that can be intensified under furrow irrigation, which enhances particle translocation and the formation of clay-rich zones that restrict deep percolation. In arid and semi-arid soils, ongoing monitoring and management of carbonate accumulation are critical, as high carbonate accumulation can restrict infiltration and alter hydrologic pathways. Routine soil testing for residual nitrate should be incorporated into fertilizer planning to better synchronize applications with crop demand and minimize surplus nitrogen available for leaching. While tillage management itself did not produce significant differences in this study, practices that enhance soil structure, such as reduced tillage, residue retention, and organic amendments, remain valuable for maintaining porosity and water regulation. Finally, long-term monitoring of both shallow and deep groundwater is recommended to track temporal trends in nitrate dynamics and evaluate how management and soil properties evolve together over time.

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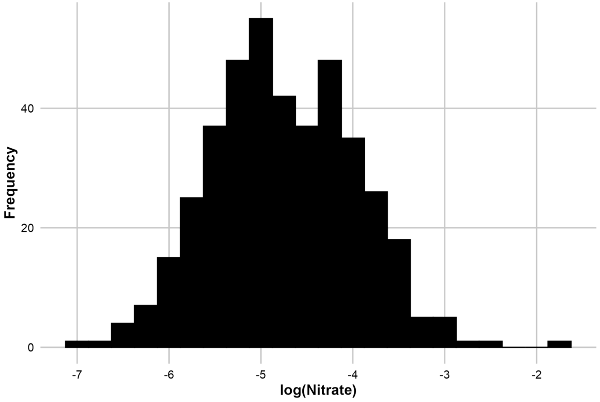
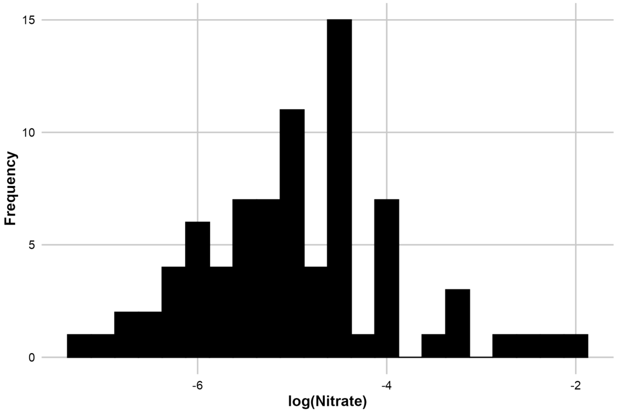
APPENDICES

APPENDIX A: DIAGNOSTIC PLOTS

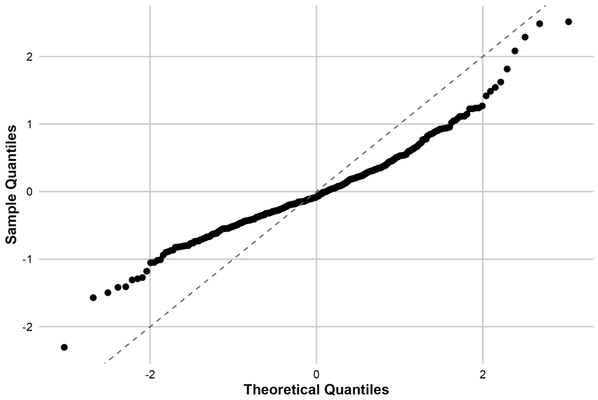
Histogram of log(Nitrate) – South Platte Basin



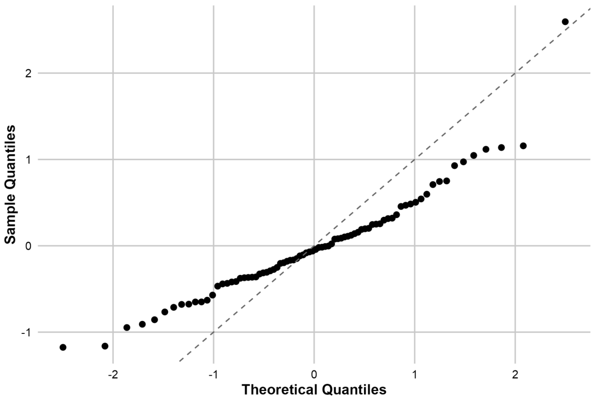
Histogram of log(Nitrate) – Arkansas Basin



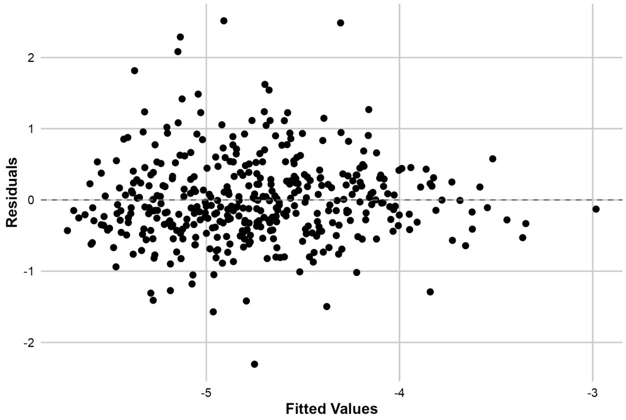
QQ Plot of Residuals – South Platte Basin



QQ Plot of Residuals – Arkansas Basin



Residuals vs Fitted Values – South Platte Basin



Residuals vs Fitted Values – Arkansas Basin

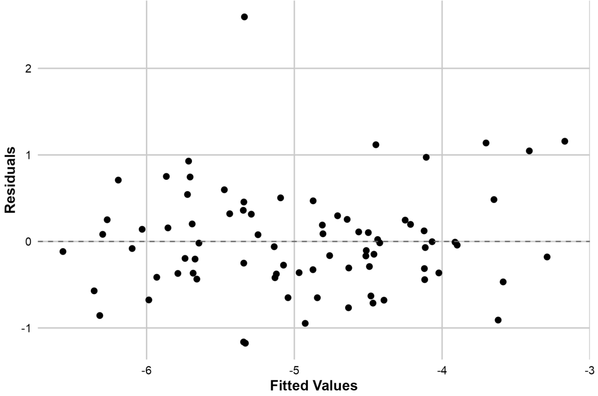


Figure A.1. Diagnostic plots for the linear mixed-effects models predicting log-transformed nitrate concentration (log(NO3−)log(NO3−)) for the South Platte (CU1) and Arkansas (CU2) basins.

For CU1, residuals were evenly distributed with limited deviation from normality, indicating that model assumptions were well satisfied. The histogram of log-transformed nitrate shows an approximately normal distribution, confirming that the transformation effectively stabilized variance.

In contrast, CU2 exhibited greater residual variability and modest departures from normality, likely due to the smaller sample size and shorter record length (2 years vs. 10 years). These diagnostics suggest that the CU1 model is statistically robust, whereas CU2 highlights the influence of limited temporal coverage and pedologic variability on model fit.