

IMPACTS OF VERY TALL STUBBLE ON PULSE CROP MORPHOLOGY AND
PRODUCTIVITY IN THE NORTHERN GREAT PLAINS

by

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ABSTRACT

Soil water conservation is crucial for productivity of dryland agricultural systems in the semiarid Northern Great Plains (NGP). Erosion concerns are prevalent among pulse crop producers across this region due to lack of post-harvest crop residues. Field-scale trials examined very tall (>60 cm) versus short (<20 cm) cereal stubble at Geraldine and Moccasin, MT, 2024. A plot-scale study in Bozeman and Moccasin, MT, in 2024, assessed pulse crop morphology and productivity in tall (>45 cm) versus short (<10 cm) stubble under rolled and unrolled treatments. Field-scale results showed increased overwinter soil water storage in tall stubble at Geraldine, with observed increases in chickpea (*Cicer arietinum* L.) biomass, seed yield, plant height, and basal pod height in tall stubble. However, a higher clay content within the tall stubble boundary likely contributed to these observed increases. For field pea (*Pisum sativum* L.) at Moccasin, only basal pod height increased in tall stubble. Tall stubble provided greater soil coverage pre-seeding and post-harvest, likely mitigating wind erosion risks. At the plot scale, basal pod height increased in tall stubble for chickpea (9.2%), lentil (*Lens culinaris* Medik.) (14%), and pea (7.2%) at Bozeman, improving harvestability. Chickpea plant height increased by 10%. At Moccasin, lentil basal pod height increased by 19%. Chickpea biomass increased by 17% in tall stubble at Bozeman only, with no biomass differences observed for lentil or pea at either site. Lentil yield at Bozeman increased by 10% in tall stubble, with no other yield differences observed. A rolling treatment effect was observed for chickpea biomass at both locations, increasing by 47% and 18% in the tall*rolled treatment compared with the short*rolled treatment at Geraldine and Moccasin, respectively. Notably, lentil plant density decreased in tall stubble by 12% at Bozeman. Importantly, it was observed that tall stubble integrity was greater at field- than plot-scale, where various plot-scale activities knocked down a much greater proportion of tall stubble. These results highlight the variable effects of tall cereal stubble on pulse crops, where tall stubble management generally offers agronomic and conservation benefits for dryland cropping systems in the NGP.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

The western portion of the northern great plains (NGP) of North America is semiarid with a continental climate, experiencing short, hot summers; long, cold winters; strong winds; and highly variable, unpredictable precipitation (Padbury et al. 2002). Soil water conservation and water use efficiency (WUE), defined as dry matter grain yield divided by the summation of soil-water depletion and total precipitation from seeding to harvest (Miller et al. 2002), are dominant priorities among agricultural producers (Tanaka et al. 2010). Efficient use of limited water in the semiarid regions of the Great Plains is critical to ensuring productive dryland cropping systems (Nielsen et al. 2005). At the turn of the 20th century, many producers in the region used summerfallow to recharge soil water. From 1916 to 1970, scientists saw fallow efficiency (the percentage of precipitation stored as soil water at the point of seeding) increase from 19% to 35% as intensive tillage practices were replaced with conservation tillage (Peterson et al. 1996). An additional 5% increase in fallow efficiency was seen with the advent of no-till farming, ostensibly capping fallow storage efficiency at a maximum of 40%. Nonetheless, summerfallow practice represents inefficient use of precipitation, degrades soil quality, and increases risk of soil erosion (Tanaka et al. 2010; John et al. 2017). Erosion is not a new concern for the Great Plains, as much of its southern region suffered from extreme wind erosion during the dust bowl of the 1930's (Tanaka et al. 2010). However, a new technology – stripper harvesting – allows producers to leave full-length crop stubble upright post-harvest while increasing combine efficiency and reducing fuel consumption (NRCS, 2023). Additionally, improved microclimate effects from tall stubble have been shown to be advantageous in dryland cropping systems, as soil water evaporation in tall wheat (*Triticum aestivum* L.) stubble was reduced importantly compared to short or cultivated wheat stubble (Cutforth and McConkey 1997). Finding ways to protect soil from erosion risk after pulse crop harvest is key to securing this nearly \$300+ million annual market for Montana pulse growers and the pulse crop processing industry (USDA 2023).

This research project had two components:

1. Field-scale stubble management for water-use efficiency. This research tested the idea that tall stubble would increase both soil water storage and supply to the subsequent crop. Accordingly, this component aimed to quantify the differences in snow-water storage and WUE of a pulse crop planted in two wheat harvesting scenarios; traditional short cereal crop stubble (<25 cm) and full-length stubble via a stripper harvester (>65 cm). This research was conducted at field-scale in collaboration with two producers located in central Montana, Jeremy Grove of Moccasin, and Chris Diekhans of Geraldine.
2. Plot-scale stubble management for pulse crop response. This component tested the idea that tall stubble improves pulse response relative to short stubble. Accordingly, this research measured chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* L.), and pea (*Pisum sativum* L.) crop morphology and seed yield in short vs very tall cereal crop stubble. This research was conducted near Bozeman and Moccasin, including short (10 cm) and very tall (>40 cm) replicated strips of contrasting cereal crop stubble heights bisected with rolled and unrolled treatments for chickpea, lentil, and pea.

1.2 Literature Review

1.2.1 Stripper Harvesting

The first stripper harvester entered the market in 1990 (Shelbourne Reynolds Engineering), manufactured by a British company, Shelbourne-Reynolds. A stripper harvester is a harvesting attachment that utilizes a “stripping rotor” (Fig. 1), or rotating bars with multiple rows of stripping fingers fitted on the front of the combine. As the combine moves forward, the stripping rotor spins backwards, removing the grain from the crop and deflecting it into an auger which moves the grain from the header into the combine. The grain is threshed 85% by the header; in other words, the material entering the combine is predominantly grain, wheat heads, and chaff, with minimal leaf and straw material (Shelbourne Reynolds Engineering).



Figure 1-1: Stripper harvester attachment (left) and stripping rotor (right) (<https://www.shelbourne.com/harvest/stripper-header/>)

Such harvesting results in the plant stem remaining erect and attached to the ground (Fig. 1-2), allowing producers to harvest grain without processing excess stem biomass through the combine. This reduction in biomass flowing through the combines necessitates faster operating speeds, and greatly reduced fuel consumption and maintenance costs (Pers. Comm. M. Erickson-Jones, 2024). A USDA-NRCS case study of six Montana producers showed an average reduction in fuel consumption of 4.7 l ha^{-1} when harvesting small grains (NRCS 2023). When compared to a conventional harvester, which consumes an average of 10.1 l ha^{-1} of diesel during small grain harvest, the stripper harvester had a 46.5% reduction in fuel consumption.



Figure 1-2: Stripped winter wheat stubble in Moccasin, MT. (Barnes 2023)

Conversely, conventional grain harvesters use a sickle bar to cut the crop at the desired height and then feed the cut biomass through the combine for cleaning and separation (threshing) (Fig. 1-3). The waste is then discarded out the back of the combine as chaff and straw.



Figure 1-3: Conventional draper header used for cereal grain harvest (<https://www.deere.com/en/harvesting/draper-platforms/>).

Stripper harvesters did not gain much traction in the NGP until 2012 when Shelbourne-Reynolds began production of a 12.6-m-wide (42 ft) harvester, making harvesting on large commercial wheat farms feasible. The Shelbourne-Reynolds patent, granted in 2001 (US 6,315,659 B1), expired in 2021 (Unknown Author 2001), enabling market competition. K-Hart Industries in Saskatchewan has since begun manufacturing a competitive product called *Raptor* (K-Hart Industries, Elrose, Canada). Such competition would be expected to increase the availability of stripper harvester and/or increase innovation. Pricing for the new Raptor Model 42-foot header ranges from \$130,000-150,000 USD, similar to Shelbourne-Reynolds (pers comm., B. Linker and C. Doheny).

Stubble Microclimate and Crop Response

Tall stubble has shown benefits for cropping systems in research studies carried out in Swift Current, Saskatchewan, through increased yield, increased WUE, and improved microclimate (Cutforth et al. 1996; 2002). A four-year study At Swift Current, SK showed a 6% yield increase of spring wheat when sown in tall stubble (30cm) compared to short stubble (15 cm) (Cutforth et al. 1997). Cutforth et al. 2002 showed that pulse crops (chickpea lentil pea on average increased both yield and WUE when seeded in tall cereal stubble compared to short cereal stubble by 8%. All stubble treatments overwintered as tall to equalize snow trapping and then the stubble height

treatments were applied in the spring before seeding, with the short stubble treatment cut by a forage harvester without windrowing to a height of 15 to 18 cm. These agronomic benefits of tall stubble were attributed to reduced wind speeds and evaporation at the soil surface (Cutforth and McConkey, 1997).

‘Microclimate’ is defined in this thesis as the specific environmental conditions that exist at the interface of the soil and atmosphere above it, which may extend 1 m or more above the soil surface. This microclimate is where the soil and the air immediately interact, influencing factors such as temperature, near surface soil water, relative humidity, wind velocity, and light intensity (Cutforth et al. 2002). Altering the soil’s microclimate to a wetter state via very tall stubble could be paramount to improving productivity among dryland cropping systems in the semiarid region of the NGP Cutforth et al. 1997 found that at 1 m above the soil surface, tall stubble reduced wind speeds by 10% when compared to short stubble. Cutforth et al. 2002 showed that microclimate and evaporation from mini-lysimeters placed near the soil surface were significantly affected by stubble height. When evaporation of mini-lysimeters was averaged across two growth periods (before and after flowering), tall stubble reduced evaporation rate by 18 and 5% respectively, when compared to short stubble. Additionally, before flowering, tall stubble reduced wind speed by 62 and 5% at 15 and 100 cm above ground, respectively, compared to short stubble.

Effects of Extra-Tall Stubble

Continued tall stubble research in southwestern Saskatchewan measured the effects of extra-tall stubble (> 45 cm) on cropping systems, aiming to represent the wheat stubble condition from stripper harvesters (Cutforth et al. 2011). When averaged across all crops reported in this study (canola (*Brassica napus* L.), chickpea, wheat), a linear increase in yield and WUE was observed as stubble height increased to 45 cm (Fig. 1-4). This yield increase is linked to increased water-use-efficiency (Cutforth et al. 2011).

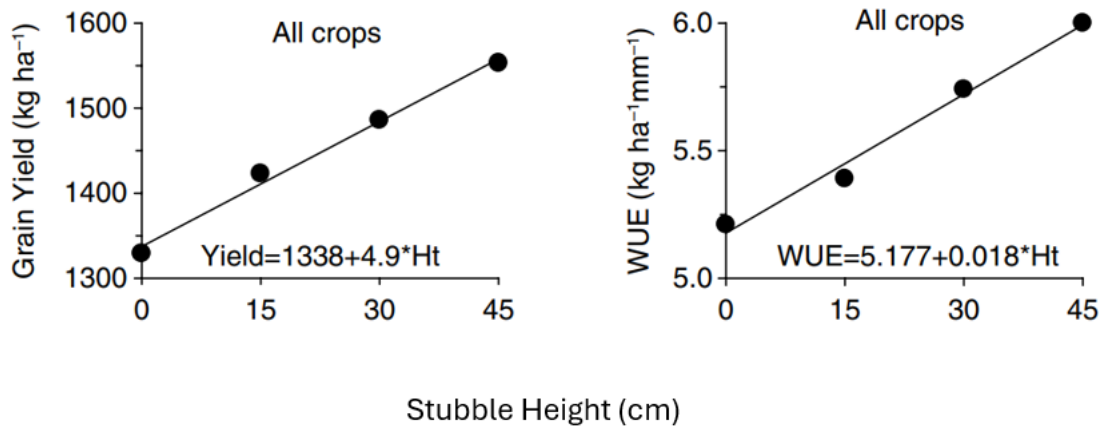


Figure 1-4: Effect of stubble height on grain yield and water use efficiency across all crops (WUE) (Cutforth et al. 2011).

All treatments (extra-tall (45 cm), tall (30 cm), short (15 cm) standing stubble, and cultivated stubble) overwintered as extra-tall (45 cm) standing wheat stubble to equalize snow trapping with the four stubble treatments. Although the effect of stubble height on cutting height of pulse crops has not been studied in Montana, it can be expected that internodes would elongate under shading such as has been reported in soybean (*Glycine max* L.) (Zhang et al. 2020), therefore increasing cutting height, a key limitation to pulse crop harvesting.

Research conducted at plot-scale in Bozeman, MT, from 2017 to 2021 compared spring dicot crops grown in 10-15 cm wheat stubble height to 40-45 cm tall wheat stubble and found that tall stubble increased grain yield in five of 13 possible comparisons, with yield increases ranging from 7 to 24% (unpublished data).

Land Rolling

Land rolling, a nearly obligate practice for pulse production in the NGP, is done by pulling large cylindrical roller over a seeded field (Fig. 1-5). This practice, commonly used by pulse producers, smooths the soil surface after seeding and push rocks and debris present on a field into the soil matrix to prevent damage to harvesters, reducing seed loss and enhancing harvest efficiency (Bourgault et al. 2024). Rollers are utilized in the spring, at various times after planting, and should exert a downward force of roughly 21 kPa (3 psi) (Kandel 2022). In more

practical terms, a Brant 351A, with a width of 51 feet and diameter of three feet, exerts a downward pressure of 18 kPa, or 382 lb per linear foot (Brandt 2024).

To fully consider the effects of tall stubble on pulse crop growth, it will be important to study pulse crop growth between erect (unrolled) and rolled cereal stubble. Concerns over land rolling remain as it increases soil compaction and significantly flattens stubble, therefore reducing the stubble's ability to trap snow, retain moisture, and reduce wind speeds (Al-Kaisi et al. 2011).



Figure 1-5: Land rolling a pulse field (<https://www.grainews.ca/crops>)

Soil Erosion Concern with Pulse Crops

Summerfallow, a practice used to recharge soil water, has been shown to be damaging to agricultural soils (Tanaka et al. 2010). Several concerns that arose from summerfallow include increased soil salinity, decreased organic matter, and increased erosion potential (Christie et al. 1985, Janzen 2001). Pulse crop production, in rotation with wheat, has largely replaced summerfallow in many parts of Montana (Fig. 1-6) (Long et al. 2014).

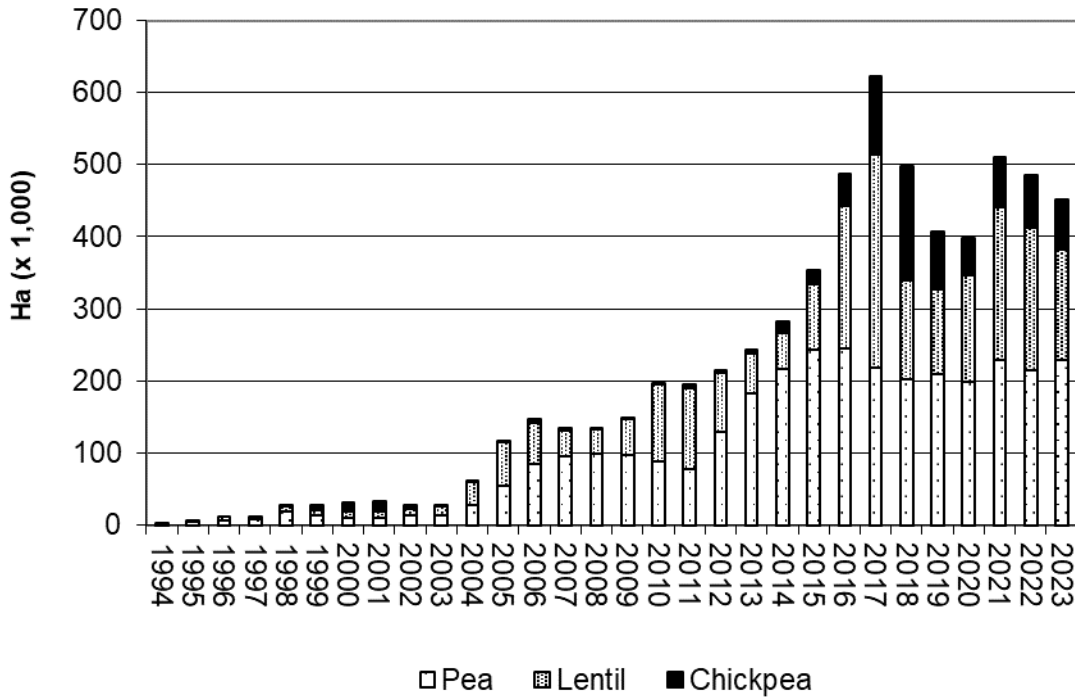


Figure 1-6: Montana pulse crop production from 1994-2023 (USDA 2023)

Pulse crops provide benefits as highly marketable crop diversification (Zentner et al. 2002; Burgess et al. 2012) that improve pest management (Krupinsky et al. 2002), increase WUE by reducing evaporation compared with summerfallow (Cutforth et al. 2002), and increase biologically sourced soil nitrogen for subsequent crops (Burgess et al. 2012). Pulse crops have a much narrower C:N ratio than cereal crops, resulting in nutrient release from pea vs. oat (*Avena sativa* L.) with pea root C:N ratios ranging from 13 to 17:1 vs. oat roots ranging from 46 to 55:1 (Wichern et al. 2007). Additionally, a fertility study in Bozeman, MT, showed that crop residue left in fallow-wheat systems and continuous wheat systems had a C:N ratio of 72:1 and 55:1, respectively, while a pea-wheat system had a crop residue ratio of 38:1 (O’Dea et al. 2015). Narrow C:N ratios encourage rapid decomposition of residual crop biomass (Beare et al. 1992). This rapid decomposition, coupled with low crop residues, can create a vulnerability for wind erosion (Cutforth et al. 2007).

As such, NRCS policy experts caution pulse growers about conservation compliance failure, as 30% ground coverage by crop residues is mandated. Mitigating erosion risk after pulse crop

harvest is critical for securing a \$300+ million annual market for Montana pulse growers (USDA 2023). It is critically important to avoid having these important benefits countered with increased soil erosion.

Since the Dust Bowl of the 1930's, wind erosion continues to pose a threat to soils across the country (Tanaka et al. 2010), including the NGP (Fig. 1-7) as it degrades aggregate structure, increases field variability, removes the most fertile part (clays, silts, and organic matter), and lowers water-holding capacity (Zobeck and Van Pelt, 2011). For most of the 20th Century, producers practiced conventional tillage where the top layer of soil would be turned in preparation for sowing crops. However, routine tillage degraded the soil structure and made it vulnerable to erosion from the elements (Huggins and Reganold, 2008).

With the advent of synthetic herbicides, no-till farming, an alternative method to conventional tillage, has become widespread across the United States. No-till farming, defined as planting crops in unprepared soil with at least 60% crop-residue coverage, revolutionized large-scale agriculture in the NGP and continues to act as a predominant erosion-control measure (Triplett and Dick 2008).

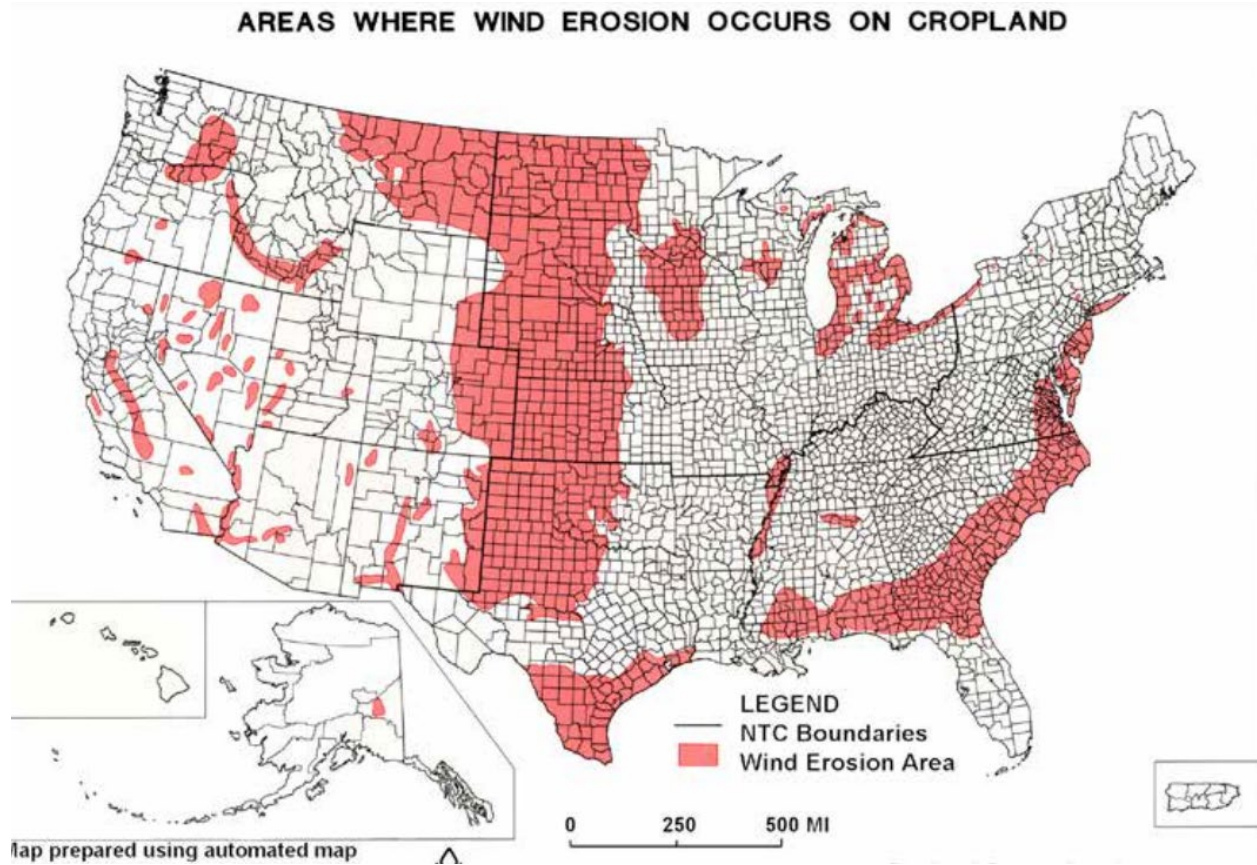


Figure 1-7: Map of the United States where wind erosion poses a threat to soil health (Tatarko et al. N.D.).

Increased cutting heights of cereals ahead of pulse crops, even by a small amount, may have a large impact on harvesting efficiency and leave sufficient crop residue to maintain >30% ground coverage (Fig. 1-8)—the minimum requirement for conservation tillage.



Figure 1-8: Post-harvest pea field near Moccasin, MT, grown in stripped wheat stubble on the left and traditional short stubble on the right (Miller 2024).

To effectively protect soil from erosion, the residue must be large enough to absorb and disperse the kinetic energy of raindrops. Only residue that is at least 2.4 mm ($3/32$ of an inch) in diameter is counted when using the Line-Transect Method (Shelton and Jasa 2009). Standing residue best defends soil from wind erosion, but any residue left, cut or standing, can be included in quantifying percent coverage as shown in Fig. 1-9 (NRCS n.d.).



Figure 1-9: Crop residue being quantified via Line-Transect Method (NRCS n.d.)

A USDA Targeted Implementation Plan (TIP), focusing on soil health in eastern MT (Henning Johns, 2019), studied the effects of poor soil residue management, and the wind erosion that can occur as a result (Fig. 1-10).



Figure 1-10: Eroded soil deposited by the wind as result of poor soil coverage in eastern Montana (Henning and Johns, 2019)

Additionally, the benefits of stripped stubble can be seen as snow-trap is drastically improved compared to cultivated stubble (Fig. 1-11). Further, it is expected that standing residual cereal crop stubble may reduce the degree of lodging that is common to viny pulse crops, which will also increase cutting height and obviate the need for land rollers to smooth soil surface after pulse crop planting. We visited with pulse growers at recent meetings of the Montana Pulse Crops Committee (22 Oct, 2024) and the Montana Grain Growers Association (3 Dec, 2024) about the potential value of an increased cutting height of 3 to 5 cm for pulses. Value estimates ranged widely relative to prevented downtime or major repair to combines from avoided soil surface obstacles. One chickpea producer estimated that a 5-cm taller cutting height in chickpea would have directly increased his net revenue by being able to harvest a higher proportion of chickpea seeds which he valued to be at least $\$115 \text{ ha}^{-1}$ ($\$46 \text{ ac}^{-1}$) during the 2024 harvest on his farm in Montana (pers. comm., P. Miller).



Figure 1-11: Snow-trap comparison of cultivated stubble (left) compared to stripped stubble (right), taken on January 23, 2024 in Moccasin, MT (Barnes 2024).

Conclusion

In conclusion, the literature demonstrates that effective stubble management may play a key role in optimizing pulse crop systems in the NGP by mitigating soil erosion and enhancing harvest efficiency. Improved stubble management may not only protect the soil surface from wind erosion but can also contribute to reduced soil water evaporation and increased moisture retention. Additionally, taller stubble has shown to increase basal pod height, increasing harvestability of pulses and minimizing harvest losses and equipment damage. As pulses provide diversity in cropping rotations and biologically fix nitrogen, improving stubble management practices to local conditions and crop types continues to be of importance to maintain sustainability and productivity to dryland cropping systems across the NGP.

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CHAPTER 2

UNDERSTANDING SOIL WATER CAPTURE AND USE BY
PULSE CROPS GROWN IN VERY TALL STUBBLE AT FIELD-
SCALE

Central Montana experiences a semiarid, continental climate characterized by cold winters and hot summers, with annual precipitation ranging from 260 to 400 mm, with nearly half of the annual precipitation occurring in late spring and early summer (Padbury et al. 2002). Summer precipitation is highly variable and often with extended drought periods. The region's soils are predominantly clay-loam with shallow gravel layers (40–100 cm) overlying subsurface horizons containing more than 40% coarse gravel, which can extend to depths of 1.5 to 10 m (Sigler et al. 2018).

Summerfallow, a practice used over the last century by dryland producers of the NGP, leaves soil uncropped for 14 to 21 months, depending on winter or spring wheat, to store soil water for a subsequent crop (Tanaka et al. 2010). The use of summerfallow in the NGP peaked in 1971, and has steadily declined since, coincident with an extraordinary period of high crop prices due to a global shortage of wheat (*Triticum aestivum* L.) (Trager 1975). The decline in summerfallow area was continued with the advent of no-till farming in the NGP (Tanaka et al. 2010). While producers saw an increase in fallow water storage with the use of conservation tillage, which ensures at least 30% of the soil surface be covered by crop residue, it was ultimately no-till farming, which leave > 60% soil coverage, that maximized soil water storage in fallow systems. No-till methods became widespread across the NGP in the 1990's and 2000's when the use of glyphosate, a chemical herbicide, became much more affordable due to its patent expiration in 1990. However, it became apparent that wheat-fallow systems, the predominant cropping system across the NGP, contributed to soil degradation through the loss of organic matter, destruction of soil-aggregate structure, and increased vulnerability to wind erosion (Janzen 2001). Because of this, alternatives to continuous wheat-fallow systems became necessary to ensure long-term soil health.

Since the turn of the 21st century, pulse crops [chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), and pea (*Pisum sativum* L.)] have helped replace summerfallow across much of the region (Long et al. 2014). With 451,000 ha in pulse production across Montana in 2023 (Fig. 1-6) evaluated at 374 million USD (USDA 2023), pulse crops play a crucial role in Montana's agricultural economy and productivity. As nitrogen-fixing legumes, they provide an important role in agronomic systems by offsetting reliance on synthetic fertilizers and increasing crop diversity, increasing energy-use efficiency, and economic resilience (Miller et al. 2002; 2015; Burgess et al. 2012). Additionally, pulse crops provide an important source of protein and nutrients for both human consumption (Lal 2017) and livestock feed (McVay et al. 2013).

A key vulnerability for pulse crop production can be too little surface crop residue to protect soil from wind erosion, which was increasingly evident during the recent 2020-22 drought in central and northern Montana (pers. comm., S. Tallman, Aug 2021). In Sep 2022, Perry Miller visited with two farmers in central Montana who had grown pulse crops for many years and were phasing them out of their crop rotations completely for fear of soil loss and failed compliance with Regenerative Agriculture (RA) markets, which require high soil coverage with crop residues at all times. Considering the greatly increased reliance on biological N sources (i.e. legumes) in RA, it is doubly surprising to hear of experienced pulse crop growers voiding their farm of this valuable class of crops that contributes to biological soil N.

Stripper harvesters may help to solve this problem as stubble management is essential for reducing soil erosion and conserving soil water in dryland agriculture, particularly in semiarid regions of Montana, where water availability is a primary constraint on crop production (Tanaka et al. 2010). Taller standing residue reduces wind velocity at the soil surface, minimizing the detachment and transport of soil particles. Additionally, standing stubble acts as a physical barrier that traps snow and increases soil water retention (Caprio et al. 1981).

Stripper harvesting is a relatively new technology that leaves full length crop stubble intact in the field, which could improve erosion control, soil water capture and crop water-use efficiency (WUE) by creating a more favorable microclimate (Cutforth et al. 2002). The research objectives for this study were to:

1. Measure soil water capture from snow trap and growing season crop WUE comparing very tall to short stubble.
2. Measure pulse crop morphology and yield when grown in very tall vs. short stubble.

Methodology

2.2.1 Field Site Description

The two locations for this study were located on private farm fields with over a decade of no-till soil management and a diverse crop rotation history including cereal and pulse crops. One field site is managed by Chris Diekhans, located near Geraldine, MT (47.685 N, -110.226 W), and a second site is managed by Jeremy Grove, located near Moccasin, MT (47.070 N, -109.898 W) (Fig. 2-2). Table 2-1 displays season precipitation values at both locations.

Table 2-1: 2023/24 mean seasonal precipitation values for Geraldine and Moccasin, MT.

Season	Precipitation (cm)	
	Geraldine	Moccasin
Winter (Nov – Mar)	6.5	4.0
Thirty-year average (1981-2010)	8.9	6.4
Growing (Apr – Aug)	25.4	20.2
Thirty-year average (1981-2010)	26.0	26.7

The Geraldine field site consisted of a 64-ha spring barley (*Hordeum vulgare* L.) stubble field divided in half for each stubble height, where soil and crop data were collected in short (<25 cm) and very tall (>65 cm) stubble heights following a pseudo-replication protocol (Brickley et al. 2007). The short stubble was cut following stripper harvest of the entire field. Owing to westerly prevailing winds, the very tall stubble was placed west of the short stubble to minimize potential snow drifting by prevailing winds from short to taller stubble. This field was sown 4 May 2024 with *Sawyer* chickpea (large Kabuli type) at a seeding rate of 135 kg ha⁻¹. A 20-m wide K-Hart (K-Hart Industries, Elrose, Canada) no-till disk drill was used at a 30.5-cm row

spacing. Prior to engagement with the producer at Moccasin and following field harvest with a stripper harvester, strips of tall stubble were cut short and bailed by the producer. As a result, the Moccasin field site consisted of a single field (56 ha) of winter wheat stubble comprised of six 100-m wide strips of alternating short (<20 cm) and very tall (>60 cm) stubble heights. This field was sown on 2 May 2024 with *Montec 4152* yellow pea at a seeding rate of 196 kg ha⁻¹. A 20-m wide K-Hart double-disk opener, set to 25.4 cm row spacing, was used for the 2024 growing season.



Figure 2-2: Field maps for Geraldine and Moccasin showing sensor locations and soil mapping. Base map is NRCS mapping data courtesy of SoilWeb (UC Davis Soil Resource Lab 2024) and Google Earth. Sensor locations appear as white dots and soil map units are indicated by yellow lines with map unit names indicated. Map units at Geraldine (left panel, 0.8 km on the bottom boundary) include mostly well-drained Bearpaw-Vida for most of the field including sensor locations, with predominantly poorly-drained and very poorly-drained Nishon and Gerber in the central area. Map units at Moccasin (right panel, 0.7 km on the bottom boundary) include well-drained Danvers-Judith for most of the field, and well-drained Judith for the northwest corner (UC Davis Soil Resource Lab 2024.).

Data Collection Methods

To measure snow-water equivalence (SWE) for assessing how snow storage compared between fields with short and very tall stubble, six snow cores were taken at each of the twelve sampling

location per site via a *Federal Snow Sampler* (NRCS n.d.) twice during the winter at the Geraldine field site (22 Jan and 20 Feb 2024). While snow depth was very limited at the Geraldine site, there was insufficient snow at the Moccasin field site location to assess SWE. Twelve *Sentek Drill & Drop* probes (*Sentek* Technologies, Stepney, Australia) were installed at each field site 8 Nov 2023 so that so that the over-winter soil water gain could be accounted. The period representing over-winter soil water gain in this study began on March 12, 2024, when the Moccasin Mesonet station (Montana Climate Office) reported soil temperatures above freezing. Data prior to the soil thawing is not reported as the sensors did not collect reliable data when the ground was frozen.

To ensure accurate and representative data collection, site locations were chosen with the intent to avoid anomalous soil characteristics and provide unbiased sensor placement. The Web Soil Survey Tool (USDA 2023), provided by the USDA Natural Resources Conservation Service (NRCS), was used to identify map units at the study sites anticipated to have consistent drainage and texture before selecting sampling locations. Sensors were then located within map units dominated by well drained clay loam and fine loam soils. Notably the mapped series boundaries do not perfectly follow the visible features within this field (Figure 2-2), likely due to offset of photos used in mapping.

At Geraldine, sensors were placed within the Bearpaw-Vida map unit that comprises >75% of the study field (Figure 2-2). All series in this unit are very deep and formed in glacial till, consistent with geologic mapping of this site as glacial deposits (MBMG). Bearpaw series (Vertic Argiustolls), a very deep, well-drained clay loam, comprised 50% of this unit, with Vida series (Typic Argiustolls), a very deep, well-drained fine loam, comprising 35%. Additional soil series present in this map unit are classified as well-drained Aridic Natrustalfs and Vertic and Pachic Argiustolls (6%) and poorly-drained Typic Albaqualfs (Nishon series, 1%), indicating relatively small areas of high salinity and poor drainage (UC Davis Soil Resource Lab 2024). Nishon series soils are formed in closed depressions, with redox features indicating persistent saturation, and contain notably higher clay content, with ranges of 35-60% clay. Adjacent map units within the Geraldine field area include Nishon and Gerber. The Nishon unit dominated by poorly drained and very poorly drained Nishon and Dimmick series clayey soils (93%) as well as better drained soils (7%) with a highly saline component (2%). The Gerber unit is mostly well

drained, generally higher clay soils (99%), including a highly saline component in claypans (2%), in addition to the poorly drained and waterlogged Nishon series (1%). At Moccasin, sensors were placed within the dominant Danvers-Judith map unit that comprises >90% of the study field (Figure 2-2). This map unit includes well-drained fine loams formed on terraces and alluvial fan remnants with gravelly horizons at ~40-100 cm (UC Davis Soil Resource Lab 2024, Sigler et al. 2018). Two series comprise the unit: Danvers (Vertic Argiustolls, 65%) and Judith (Typic Calciustolls, 35%). Judith series contains shallower gravel in subsurface Bk horizons, while Danvers includes a gravel contact at over 100 cm in a C horizon.

In addition to the Web Soil Survey Tool, visually anomalous areas, such as steep slopes, depressions, and field edges, were avoided. The locations for the sensors were then randomly selected from the remaining area by dividing the study site into a uniform 50 x 50-m grid, which ensured spatial coverage across the entire study site, omitting 100 m from all field edges, and provided a basis for randomized locations while minimizing the potential for bias. GPS coordinates were recorded via an Emlid Reach RS2+ (Emlid Tech, Budapest, Hungary) to mark each sensor location. These probes measured volumetric soil-water content to a depth of 60 cm, with six individual depths reported below the soil surface (5, 15, 25, 35, 45, and 55 cm). These probes were removed prior to spring planting to avoid mechanical damage to the probes from farming equipment on 8 Apr, 2024.

Additionally, at the Geraldine site, the depth of moisture in the soil profile was estimated 9 Apr 2024 with a Paul Brown Probe (Brown 1959), a 1.1-m long blunt rod which measures the depth of moist soil from the soil surface due to overwinter soil water recharge. Six insertions from the Paul Brown Probe were taken at each sensor location and averaged for a soil water depth (operator specifications: 1.50 m tall, weighing 77 kg). This data was used in conjunction with the *Sentek* probes to estimate differences in soil-water content between stubble types. Useful Paul Brown Probe measurements were unable to be taken at the Moccasin field site as there was a shallow cobble stone layer that could not be penetrated by the hand probe.

To measure temporal patterns in soil water during the growing season, the same 12 *Sentek* soil water probes were placed back in the soil on 14 May 2024 within 3 m of the original location while avoiding the disturbed soil column from the exact original location. Sensors were installed by auguring a hole in the ground, then sliding the sensors into the hole and flush with the ground.

A slurry was used for the spring installation of *Sentek* sensors to improve sensor-to-soil contact by using a one-to-one mixture of silt and water. *Sentek* sensor probes were chosen at random for each site location and season (Table C1). The probes were left for the duration of the growing season at each location, then removed once the crop reached physical maturity (the plant pods had reached their maximum dry weight as judged by visible yellowing of >90% of pods) and prior to producer harvest. *Sentek* sensors were removed 30 Jul and 13 Aug 2024 at Moccasin and Geraldine, respectively. The *Sentek* sensors were used to compare differences of in-season volumetric-water content of the soil profile between short and very tall stubble. Each sensor was calibrated for a silty-clay loam (the most representative setting for each field site's soil structure) soil structure ($f(x) = 1.072x^{0.209} - 1.169$, $R2 = 0.867$, $CV = 0.014$) where volumetric soil-water content was measured and reported as volume of water per volume of soil (water³ soil⁻³). To put volumetric soil-water content in an agronomic perspective, it was converted into rainfall equivalence, where the volumetric soil-water content was multiplied by the thickness of the soil profile measured. Rock and debris found in the soil reduces sensor-to-soil contact, which can greatly influence the *Sentek* sensor data. Due to the thin and variable fine textured horizons of the Judith soil series (UC Davis Soil Resource Lab 2024), and in an effort to avoid sensor contact with any gravel/cobble, only depths 5, 15, 25 and 35 cm are used for data analysis for the winter and growing seasons at Moccasin. Winter series data reported from *Sentek* sensors starts on 12 Mar, 2024, aiming to capture the thawing of the soil and snow-infiltration.

Water use efficiency for pulse crops grown in cereal stubble was defined for this study by the following equation: $WUE = \left(\frac{\text{Dry Matter Grain Yield}}{\text{Water Used}} \right)$. Total plant biomass and grain yield samples were taken to measure pulse crop performance between short and very tall stubble and to explicitly calculate WUE in the context of differential overwinter soil water capture.

'Water use' was calculated as the difference in soil-water content (from *Sentek* probe data) between the start and end of the growing season, plus precipitation received between seeding and pulse crop harvest. Note that it is possible that soil water use was underestimated slightly since these crops are known to root in excess of 60 cm in depth (Miller and Holmes, 2012). Geraldine precipitation data was obtained using the Prism Model from OpenET (OpenET 2025), as no weather stations were present sufficiently near the Geraldine field site. Moccasin precipitation

data was obtained from the Moccasin Agrimet station located at the Montana State University Central Agricultural Research Center (6 km from Moccasin field site).

At physiological maturity, above-ground biomass samples were collected at each of the 12 sensor locations per field site. Biomass samples were taken on 30 July and 13 Aug 2024 at the Moccasin and Geraldine locations, respectively, within three meters of each *Sentek* sensor where eight one-meter-long row samples were cut flush with the soil surface by hand with a serrated *Harvest Knife Weeding Sickle* (Zenport, Sherwood, OR). The hand-harvested area was measured by taking into account the row spacing of the crops rather than using a square-meter quadrant. Twelve plants were randomly selected from each sample and morphology measurements taken immediately in the field. Each of the 12 plants were laid flat on the ground against a measuring tape where two measurements were recorded: total plant height and the height from the bottom of the plant stem to the first pod. Once morphology measurements were recorded, all harvested biomass samples were placed in cloth bags and transported to MSU-Bozeman's campus for further laboratory analysis. Finally, the *Sentek* sensors were removed from the field site on 30 Jul and 13 Aug 2024 at Moccasin and Geraldine respectively. Within 24 hr of harvest, the above-ground biomass samples were placed in a dryer at 50 °C for 72 hr, then mechanically threshed through a Wintersteiger A-4910 combine (Wintersteiger USA, Salt Lake City, UT) for yield data.

Statistical Analyses

At Geraldine, pseudo-replication was used for t-test determination by randomly choosing sampling locations from a prescribed 50-m grid pattern (Bricklemyer et al. 2007). At Moccasin, despite the appearance of a replicated trial, the stubble blocks were systematically alternated and therefore not randomly assigned. So, essentially the same pseudo-replication sampling was completed as at Geraldine, but in a stratified manner with two sampling sites per stubble block. All statistical procedures were conducted using R 4.4.1. Linear regression models (base R) were used to assess the effect of stubble height on the following response variables: biomass, basal pod height, plant height, seed yield, *Sentek* soil-moisture, and snow-water equivalent (SWE). The formula for the model is: Response variable = $\beta_0 + \beta_1 \cdot \text{stubble height} + \epsilon$, where β_0 = the intercept, β_1 = the coefficient for stubble height, and ϵ = error term. Statistical significance was determined on a 95% confidence interval ($P < 0.05$).

Results and Discussion

Soil Water

The 2023/24 winter in Central Montana was below average in terms of snowpack and precipitation. According to the Montana Climate Office (University of Montana), 4.0 cm of precipitation from November-March, only 63% of the 30-year mean (1981-2010). At Geraldine, 6.5 cm of winter precipitation occurred from November-March, only 73% of the historic average (1981-2010). Many environmental factors can affect snowpack and its conversion into soil water, with snowfall variability, frequency, and density being of key importance (Ries and Power 1981). If the annual snowfall is well below average, little change is expected in stored soil water content. The 2023/24 winter led to a sparse, sporadic snowpack that was inadequate to reliably measure SWE during site visits at Moccasin. While snow sampling occurred at Geraldine due to a slightly larger snowpack, there were no measured differences in SWE ($P=0.248$) (Table 2-2). Winter snowpack can vary strongly from place to place and year to year in Montana. For example, the 2022/23 and 2024/25 winters had large snowpacks, unlike the 2023/24 winter. From the 2022/23 and 2024/25 winters, from 1 Nov to 16 Jan, both years reported 2.3 cm of precipitation (U.S. Bureau of Reclamation). In comparison, the 2023/24 winter only reported 1.2 cm of precipitation for the same dates. In a much snowier winter, SWE measurements taken 16 Jan 2025 at the Central Agricultural Research Center in Moccasin measured roughly 0.25 cm of SWE gained per 1.0 cm increase in stubble height (pers. comm., S. Fordyce, Jan 2025). This trend was also seen when Caprio et al. 1981 recorded snowpack data during the 1976-78 winters across the state of Montana, investigating snow barrier potential for harvesting moisture. Four non-Chinook site locations included in that study were Big Sandy, Bozeman, Winifred-Moccasin and Moccasin-Denton. The 1976-77 winter showed an average increase in snow depth of 3.5 cm in tall vs. short stubble and SWE measurements showed an average of 0.6 cm increase in water. The 1977-78 winter followed the same trend with an average increase in snow depth and SWE of 5.6 cm of snow and 1.3 cm of water, respectively, in tall over short stubble. These findings can be illustrated in Fig. 2-3, taken in Moccasin on 23 Jan, 2024, where the increased snow-trap potential of tall stubble is clearly visible. While SWE measurements were not able to

be reliably taken at Moccasin, the images below (Fig. 2-3) show a visual difference in snow cover between short (left) and tall (right) stubble.



Figure 2-3: Snow coverage in short vs tall stubble. Pictures taken at Moccasin, 23 Jan, 2024 (Barnes 2024).

Spring soil water measurements (Paul Brown probe) were not taken at Moccasin due to a shallow cobble layer below the soil surface (Sigler et al. 2018) that the probe could not penetrate. Spring sampling (9 Apr 2024) of probe depths in short vs. very tall showed no difference ($P=0.39$) in soil water depths at Geraldine (Table 2-2).

Table 2-2: Snow water equivalent (SWE), measured over two sampling dates (22 Jan and 20 Feb 2024), and Paul Brown Probe measurements (taken 9 Apr 2024), in short vs. very tall stubble at Geraldine, MT.

Stubble Height	SWE	Paul Brown Probe depth
	————— cm —————	
Short	4.5 a	74 a
Very Tall	5.1 a	79 a

Note. Significance of treatment effects evaluated at $\alpha = 0.05$. Common display letters within a column denote the individual means do not differ.

Volumetric water content of the soil profile was reported both during the late winter (12 Mar–8 Apr, 2025) and the growing season (16 May–13 Aug) to estimate soil water levels (Table 2-4). Data reported for winter aims to capture the thawing of the soil and water infiltration into the soil profile as the snowpack melts, such as it was, and data reported from the growing season aims to capture soil water levels during the growing season. Tables 2-4 to 2-7 display time series data which represents rainfall equivalence averaged across the entire measured soil profile and stubble height, with error bars representing one averaged standard deviation of the mean for six field locations and all depths (six at Geraldine, four at Moccasin). At Geraldine, winter soil water was significantly higher ($P < 0.01$), with tall stubble exceeding short stubble by 3.3% (Fig. 2-4, Table 2-4). Soil sampling in the spring of 2025 found a higher clay content within the tall stubble portion of the study site, consistent with soil mapping, especially considering mapping boundary offset from visible features (Figure 2-2). Fig. B1 indicates a greater soil water storage capacity in these soils, likely due to the increased clay content within the tall stubble area, as soil water is consistently higher at each individual depth.

To put this in perspective of available water for crop use, a rainfall equivalence was calculated based on the depth of the *Sentek* probe. This 3.3% increase in soil water translates to an additional 2.0 cm of plant available water at the start of the growing season. A study conducted in Mandan, ND (Ries and Power 1981) showed a 7.1 cm increase in soil-water storage over winter when increasing wheatgrass stubble height from 30 to 60 cm. Increasing stored spring soil water by 2.0 cm likely had a meaningful impact on pulse crop performance as shown in Table 2-6. Miller et al. (2002) reported an increase of 1.4 cm of stored spring soil water translated to a 210 kg ha⁻¹ yield increase in field pea grown in the prairie region of Saskatchewan.

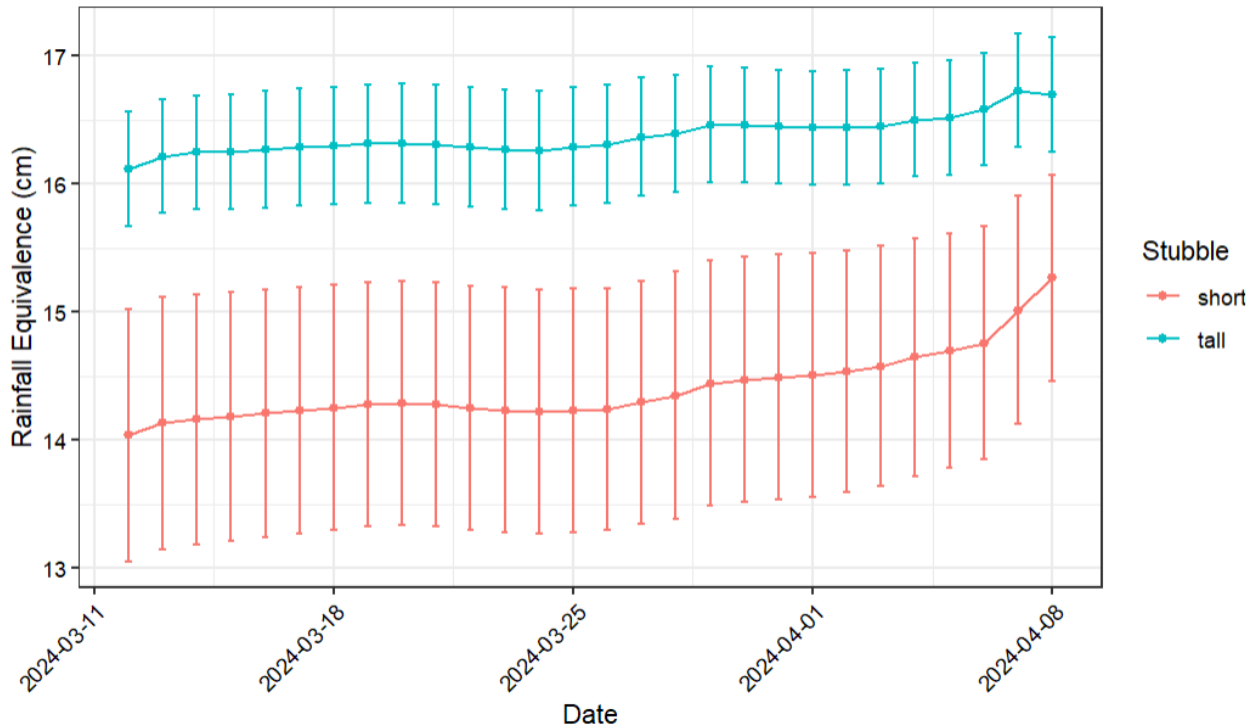


Figure 2-4: Time series plot of rainfall equivalence to a depth of 60 cm averaged across sensors by stubble type at Geraldine, MT from 12 Mar to 8 Apr, 2024. Error bars represent one standard deviation of the mean of six locations and six depths.

At Moccasin, tall stubble showed a slight decrease of 0.7% (0.2 cm water equivalence) over a 40 cm profile during the winter. Despite the strong statistical significance ($P < 0.01$, Fig. 2-5) due to the closely aligned trends between the two stubble heights, the small reduction in water is unlikely to have a meaningful impact on crop performance. Tables 2-5 and 2-7 also display manually measured soil water data (labeled “stubble (manual)”, Poole 2025) translated to rainfall equivalence at a depth of 30 cm at the Moccasin site only. This data from Poole 2025 was derived from samples that were manually collected and oven dried for gravimetric soil water content over a 30 cm profile. The lower soil water data collected via *Sentek* sensors vs. manually measuring soil water.

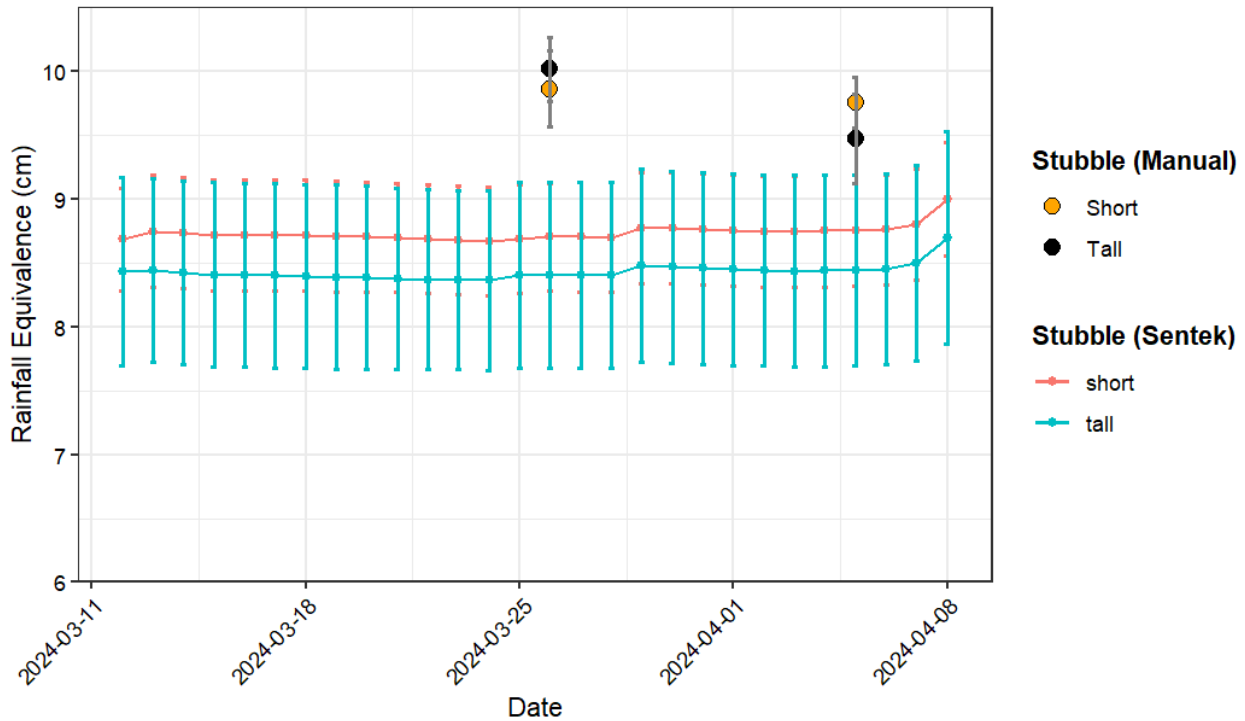


Figure 2-5: Time series plot of rainfall equivalence to a depth of 40 cm averaged by sensor across stubble type at Moccasin, MT from 12 Mar to 8 Apr, 2024. Error bars represent one standard deviation of the mean of six locations and four depths.

During the growing season, no difference was observed for soil water at Geraldine (Fig. 2-6). At Moccasin, a small decrease in mean soil water was seen in tall stubble (0.4%, Table 2-4). Again, this statistical significance is likely due to the closely aligned trends of soil water based on stubble height, and very high ‘n’ for soil moisture readings (Fig. 2-7). This 0.4% decrease translates to a decrease of 0.2 cm of water, likely having little effect on the crop. Additionally, shown in Appendix A, Figures A1-A4 illustrate the variation each sensor reported with time series rainfall equivalence plotted for each sensor over time. Figures B1-B4 in Appendix B show the variation in rainfall equivalence for each depth measured by the sensors, averaged across all sensors. Fig. B3 displays soil water storage increasing at shallower depths in short stubble at Moccasin over winter, contradicting the notion that tall stubble increases soil water storage. This observation reflects the low amount of water delivered as snow in the 2023-2024 winter (~6 cm SWE) relative to water stored in the soil as of the prior fall (~12 cm), and the cumulative retention of snow-derived soil water over the course of the winter (~4 cm) (Poole 2025), and

may indicate that rapid melting of snow in the short stubble ensured infiltration into the soil. However, it is also visibly evident from Fig. B4 that during the growing season, tall stubble retained higher soil water content at intermediate depths (15 and 25 cm).

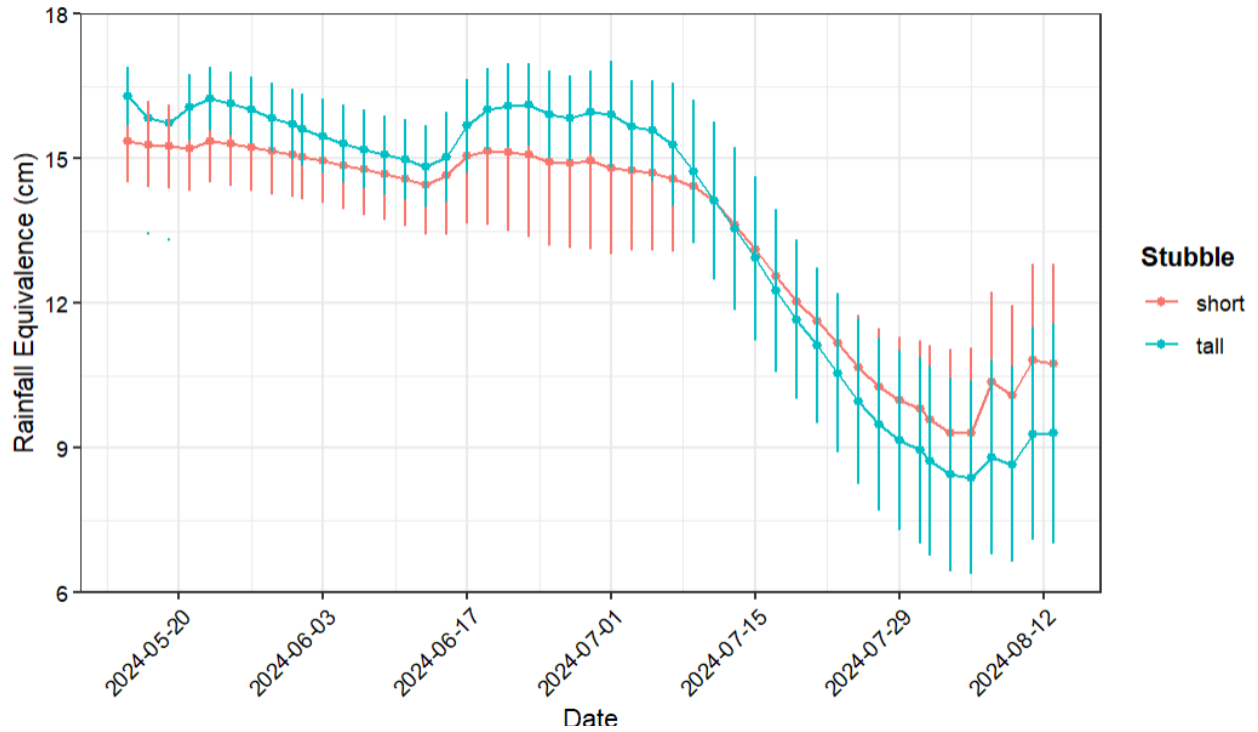


Figure 2-6: Time series plot of rainfall equivalence to a depth of 60 cm averaged across sensors by stubble type at Geraldine from 16 May to 13 Aug, 2024. Error bars displayed represent standard deviation.

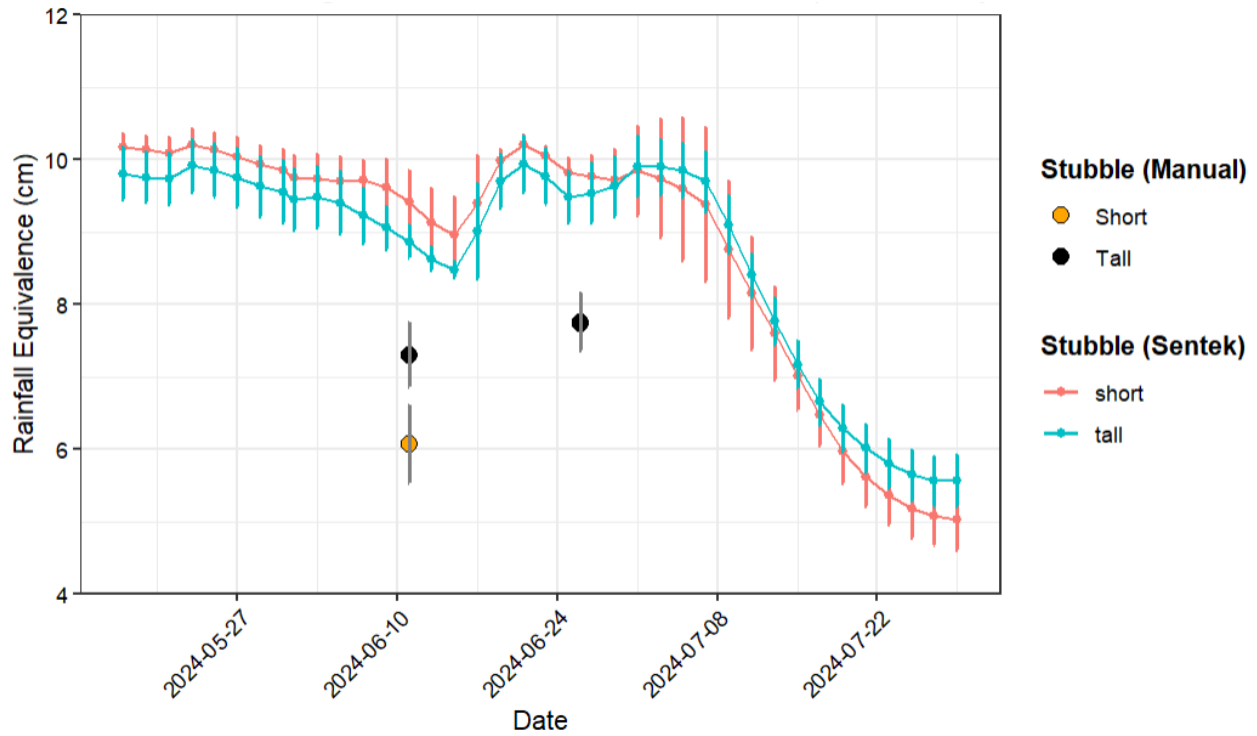


Figure 2-7: Time series plot of rainfall equivalence to a depth of 40 cm averaged across sensors by stubble type at Moccasin from 16 May to 30 July, 2024. Error bars displayed represent standard deviation.

Table 2-3: ANOVA table for *Sentek* soil water response to stubble height during the late winter (12 Mar – 8 Apr, 2024) and growing season (16 May – 13 Aug, 2024) at Geraldine and Moccasin, MT.

Location	Season	df	Mean Sq	P-value
Geraldine				
	Winter	1	654	<0.01
	Growing	1	7.5	0.33
Moccasin				
	Winter	1	11.6	<0.01
	Growing	1	22.2	<0.01

Table 2-4: *Sentek* soil-water data comparing short to very tall stubble for both late winter (12 Mar - 8 Apr, 2024) and growing season (16 May – 13 Aug, 2024) time periods at Geraldine and Moccasin, MT.

Location	Stubble Height	Volumetric Soil Water Content		Rainfall Equivalence	
		— cm ³ water cm ⁻³ soil —		——— cm ———	
Geraldine		Winter	Growing	Winter	Growing
	Short	0.240 b	0.227 a	14.4 b	13.6 a
	Very Tall	0.273 a	0.228 a	16.4 a	13.7 a
Moccasin					
	Short	0.218 a	0.223 a	8.7 a	8.9 a
	Very Tall	0.211 b	0.219 b	8.5 b	8.7 b

Note. Significance of treatment effects evaluated at $\alpha = 0.05$. Common display letters within a column denote the individual means do not differ. Rainfall equivalence represents height of soil water within the soil profile based on 60 cm and 40 cm probe depth at Geraldine and Moccasin, respectively.

Pulse Crop Productivity

At Geraldine, measured chickpea parameters (biomass, basal pod height, plant height, and seed yield) were markedly greater in very tall vs short stubble (Table 2-6). Biomass and seed yield increased 2.44 Mg ha⁻¹ ($P=0.001$) and 959 kg ha⁻¹ ($P=0.0041$), respectively, in very tall vs short stubble (Table 2-6). At a market price of 22 USD per bushel (Northern Ag Network 2024), a 959 kg ha⁻¹ seed yield increase equates to ~770 USD of additional revenue generated per hectare farmed.

Cutforth et al. (2011) showed a linear increase ($P = 0.10$) in seed yield for chickpea as stubble height increased from cultivated to very tall (> 45cm), with yields increasing from 1200 to 1430 kg ha⁻¹. Further, these researchers reported an average seed yield increase of 9% across all pulses when grown in tall (36 cm) vs short (15 cm) stubble. While the producer of this field did not have quantitative data to share from machine harvest, he did note a drastic increase in yield between tall and short stubble, estimating >50% increase in seed yield in tall stubble (pers comm., C. Diekhans, Oct 2024). However, with such a drastic difference in yield measured at this study site in favor of tall stubble (74% increase), it is likely that other agronomic factors influenced yield in addition to stubble height. Soil sampling in the spring of 2025 confirmed that soils within the tall stubble boundary are higher in clay content, making increased soil water retention likely and conforming to expectations from soil mapping (Fig. 2-2). Consistent with

redox features in the mapped soils indicating chronic saturation (Nishon and Dimmick series), the subsequent wheat crop suffered from poor survival due to excess wetness (pers. comm., C. Diekhans, April 2025).

Morphologically, plant height and basal pod height increased by 12.3 ($P < 0.001$) and 4.0 cm ($P = 0.014$, Table 2-6). Cutforth et al. (2002) showed during one study year (1997) that basal pod height was affected by stubble height, increasing across pulses by 4.6 cm when grown in tall (36 cm) vs. short (15 cm) stubble.

Huggins and Pan (1991) grew winter lentil and pea in northern Idaho and observed longer internodes and overall vine length when grown in tall stubble. That study linked these positive morphology responses to greater soil water conservation as soil water levels in the first 15 cm of the soil profile were 20% higher in tall (35 cm) vs short (5 cm) stubble. Additionally, that study concluded that internode elongation was also influenced by a shading effect of tall stubble, which reduced photosynthetically active radiation and red/far red ratios by 17% and 22%, respectively, from the top of the standing stubble (35 cm) to the soil surface.

While difficult to quantify, the increased height in basal pod increases harvest efficiency, saving producers time and wear-and-tear on machinery, and avoids costly repairs and downtime associated with catastrophic equipment damage from ingesting stones or other obstacles in the combine at harvest. We consulted with several pulse growers to attempt valuation of a taller cutting height (Montana Pulse Crops Committee, 22 Oct, 2024; Montana Grain Growers Assoc., 3 Dec, 2024). Most agreed that avoided machine damage and down-time could represent the largest valuation but one producer in the audience at the Montana Grain Growers Association meeting quickly estimated a potential yield increase. His assumption was that if a taller stubble height permitted him to harvest just one more chickpea pod per plant containing a single seed compared with short stubble, with a standard crop density of 30 plants per m^{-2} , and typical seed weight of 400 mg seed⁻¹, that would translate to a harvestable yield increase of 120 kg ha⁻¹, or \$97 ha⁻¹ more than in short stubble at a chickpea price of \$22 bu⁻¹.

At Moccasin, above-ground biomass, plant height, and seed yield did not differ between stubble heights, while the basal pod height was 5.8 cm greater ($P = 0.016$) in very tall stubble (Table 2-5). Again, the increase in basal pod height aids harvest efficiency and reduces damage to harvesting equipment and potentially increases harvestable yield.

While WUE at Geraldine showed an increasing trend ($P = 0.07$) in very tall stubble over short stubble, at Moccasin, no change in WUE was observed between stubble treatments (Table 2-5). Miller et al. (2002) assessed pulse crop adaptation in the NGP with over 20 location-years, and reported WUE range from 2.5 – 13.6 kg ha⁻¹ mm⁻¹ and 4.1 – 16.1 kg ha⁻¹ mm⁻¹ for chickpea and pea, respectively. The results from my study fell into the upper end of those reported ranges (Table 2-6). Additionally, Cutforth et al. 2002 found an 8% increase in WUE across all pulses grown in tall vs. short stubble.

Table 2-5: ANOVA for stubble height effects on pulse crop performance at Geraldine and Moccasin, MT, 2024.

Location	ANOVA	Basal Pod Height cm	Biomass Mg ha ⁻¹	Plant Height cm	Seed Yield kg ha ⁻¹	WUE kg ha ⁻¹ mm ⁻¹
Geraldine						
	P-value	0.01	<0.01	<0.01	<0.01	0.07
	Mean Sq	42.95	1.62E7	408.4	2.51E6	18.3
	df	1	1	1	1	1
Moccasin						
	P-value	0.02	0.90	0.49	0.62	0.89
	Mean Sq	90.86	8606	32.54	21204	0.018
	df	1	1	1	1	1

Table 2-6: Pulse crop performance means based on stubble height effects at Geraldine and Moccasin, MT, 2024.

Location	Stubble Height	Basal Pod Height cm	Biomass Mg ha ⁻¹	Plant Height cm	Seed Yield kg ha ⁻¹	WUE kg ha ⁻¹ mm ⁻¹
Geraldine						
	Short	22.9 a	2.77 a	36.1 a	1300 a	6.59 a
	Very Tall	26.9 b	5.21 b	48.4 b	2259 b	9.29 a
Moccasin						
	Short	33.9 a	5.25 a	62.1 a	1951 a	13.47 a
	Very Tall	39.4 b	5.20 a	65.4 a	2035 a	13.56 a

Note. Significance of treatment effects evaluated at $\alpha = 0.05$. Common display letters within a column denote the individual means do not differ.

Soil Erosion

There were clear visual differences in soil coverage for short vs. tall stubble. Shown below in Fig. 2-8 are two pictures taken on 14 May, 2024, at Moccasin, MT following spring planting. It is visually evident that tall cereal stubble increased residual crop biomass which can be expected to provide greater protection from wind erosion and provide adequate ground coverage following pulse crop harvest. It is also noteworthy of the potential benefits of soil erosion protection by an increase in plant height. Miller et al. (2002) reports studies from Saskatchewan documented chickpea only supplying roughly half of the soil-covering residue provided by spring wheat when grown in the same conditions. An increase in chickpea plant height by >12 cm as seen in Geraldine may provide additional soil-erosion protection, especially when combined with seeding in tall stubble.



Figure 2-8: Pictures taken of short (left) vs. tall (right) stubble at Moccasin, MT on 15 May, 2024 (Barnes 2024).

Additionally, shown below in Fig. 2-9 are pictures taken 8 Nov, 2024, that display ground coverage post-harvest in the pea field at Moccasin. Note that very little pea stubble is evident; a

majority of the soil coverage is due to the prior year's cereal stubble, emphasizing the importance of proper stubble management for erosion control.



Figure 2-9: Pictures taken of short (left) vs. tall (right) stubble at Moccasin site post pea harvest on 8 Nov, 2024 (Miller 2024).

Conclusion

This study observed a variety of effects of tall stubble, but did not support tall stubble as a control on water storage in a low snow year. At Geraldine, benefits to the pulse crop were likely an effect of clay rich soil associated with a local depression that enhanced water retention and thus benefitted biomass, pod height, and yield (but not WUE). At Moccasin, tall stubble retained greater water storage at intermediate depths during the growing season. In this case, given similar biomass and seed yield with stubble height that suggest similar transpiration, tall stubble shading may have limited evaporative loss of water from the soil, thus benefiting the crop. Additionally, chickpea plant height and basal pod height increased, with potential benefits for harvest efficiency and equipment longevity. At Moccasin, no differences in biomass or seed yield were observed between stubble treatments, though basal pod height was notably greater in tall stubble, again likely improving harvestability.

The WUE at Geraldine followed an increasing trend in very tall stubble, aligning with previous research showing WUE benefits from greater stubble height. However, no changes in WUE were detected at Moccasin. These findings suggest that field-specific environmental factors, such as

soil texture and local precipitation patterns, may influence the relationship between stubble height and soil water dynamics.

In addition to agronomic benefits, visual differences were observed with greater soil coverage in tall stubble pre-seed and post-harvest, potentially reducing wind erosion risk and providing a protective cereal crop residue layer. This is particularly relevant given that pulse crop residue provides substantially less ground cover than cereal crops, emphasizing the importance of tall cereal stubble retention for long-term soil conservation.

Overall, these results reinforce the value of stubble height management as a viable strategy for improving water retention, crop productivity, and soil protection in Montana's dryland systems. Future research should explore long-term effects across varying climatic conditions and cropping systems to further refine best management practices for sustainable dryland agriculture.

Chapter 2 References

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CHAPTER 3

EFFECT OF VERY TALL CEREAL STUBBLE ON PULSE

CROP MORPHOLOGY, YIELD, AND WATER USE

EFFICIENCY

Central Montana experiences a continental weather pattern with highly variable year-to-year precipitation with long, hot, dry periods common during the summer months. Annual precipitation ranges from 260 to 400 mm, with majority of it occurring during late spring and early summer (Padbury et al. 2002). Because of this, dryland agriculture in central Montana has traditionally been dominated by tillage-based cereal-fallow systems which utilized drought resistant crops like spring wheat (*Triticum aestivum* L.), fallow periods to conserve soil water and tillage practices to release soil-based nutrients to ensure agronomic productivity (Tanaka et al. 2010).

Summerfallow, a practice used to store soil water by leaving land uncropped for 14-21 months, peaked in 1971 across the NGP (Fig. 3-1). This change was driven by a period of high commodity prices and a collective realization that summerfallow represented lost opportunity to increase farm profitability. With the advent of annual cropping, cereal stubble management became increasingly important to increase water-use-efficiency. Starting in the 1990s, the declining trend of fallow land accelerated due to no-till farming, a practice where seeds are planted directly into undisturbed soil through remaining residue from a previous crop (Tanaka et al. 2010).

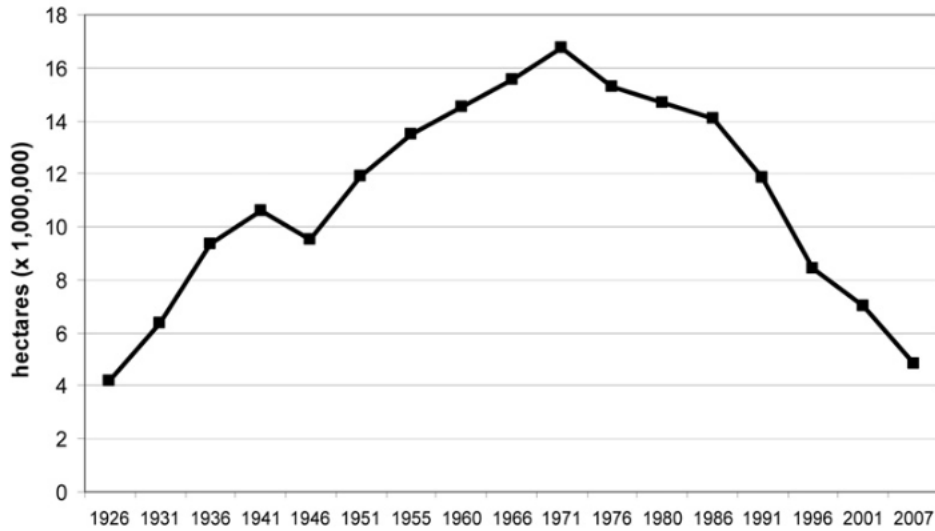


Figure 3-1: Estimated area of summerfallow land in the NGP from 1926-2007 (Tanaka et al. 2010).

Intensifying crop rotations begs crop diversification to manage various pests, a key component for increasing profitability and sustainability in agriculture (Miller et al. 2002). Additionally, the use of tall cereal stubble has been shown to trap more snow during winter months and further recharge soil water (Steppuhn 1994). Because of the importance of crop diversity for agricultural sustainability, pulse production across the NGP began to steadily increase at turn of the 21st century due to high WUE and the added benefit of nitrogen fixation (Miller et al. 2002, Burgess et al. 2012).

Cereal stubble height management plays a critical role in the production of pulse crops in central Montana, where pulse production has increased from 30,000 to 451,000 ha since the year 2000 (Figure 1-6, USDA 2023). However, the specific effects of cereal stubble height on pulse crop harvest efficiency and crop performance have not been studied in this region. Understanding these effects is crucial, as the potential evaporative demand for soil-water typically exceeds crop demand, representing the greatest limitation to dryland crop production in semiarid regions like central Montana (Hu et al. 2015). Very tall cereal stubble may also be key to managing wind erosion risk in pulse crops (pers. comm., S. Tallman, Aug 2023)

Harvestability is a common concern among pulse growers, as the header must be set low to ground to harvest the grain. In doing so, the harvester is at risk for damage caused by ingesting stones and other debris on the soil surface (Kuzbakova et al. 2022). Land rolling of pulse crops is a nearly obligate practice in the NGP to smooth the soil surface after seeding and to push rocks or other surface debris into the soil matrix (Bourgault et al. 2024). Because of this, it is important to study pulse crop responses between erect (unrolled) and rolled cereal stubble.

The effect of stubble height on cutting height of pulse crops has not been studied in Montana. One of the primary mechanisms through which stubble height may influence pulse crops is internode elongation under shaded conditions. Research on soybean (*Glycine max* L.) suggests that plants respond to shading by elongating internodes, which could lead to increased cutting heights in pulse crops (Zhang et al. 2020). Increased cutting heights of pulses, even by a small amount, may have a large impact on remaining crop residues to enable soil protection from wind erosion.

This elongation effect, combined with the presence of standing residual cereal crop stubble, may reduce lodging—another common issue in pulse production. Reduced lodging could further enhance cutting height, facilitating more efficient harvesting operations. Farmers who harvested pulse crops grown in tall stubble report that harvest efficiency increases due to reduced shattering losses and appropriate crop volume (pulse crop + weathered wheat stubble) flowing through the combine. The research objectives for this study were to:

1. To measure changes in chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), and pea (*Pisum sativum* L.) crop morphology components and crop yield and biomass response in very tall vs short cereal crop stubble.
2. To measure the same parameters comparing land rolling after seeding vs. not rolling.

Methodology

Study Site Description

In 2024, this study was conducted at Bozeman (A.H. Post Farm: 45.674 N, -111.156 W) and Moccasin, MT (Central Agriculture Research Center: 47.056 N, -109.952 W), with soil and

climate data shown in Table 3-1. The soil type at Bozeman was an Amsterdam silt loam with organic matter content of ~2.6% and pH of ~7.2 (0–0.15 m depth composite sample soil measurement; AgVise Laboratories, Northwood, ND). The soil type at Moccasin is a Judith Danvers clay loam with organic matter of ~4% and pH of ~7.1 (0–0.15 m depth composite sample soil measurement; AgVise Laboratories, Northwood, ND). Damaging hail events occurred at Moccasin on 18 and 20 June, 2024, totaling 2.5 cm in precipitation.

Table 3-1: Meteorological and soil information for field experiments at Bozeman and Moccasin, MT.

Parameter	Bozeman	Moccasin
Precipitation	mm	
Apr-Aug	230	203
30-yr Avg. (1981-2010)	250	260
Soil		
Series	Amsterdam silt loam	Judith clay loam complex
Classification	fine-silty, mixed, superactive, frigidtypic haplustolls	Fine-loamy, carbonatic, frigid typic calciustolls

Agronomy and Data Collection Methods

At Bozeman, a 1.8-m wide low-disturbance no-till disk seeder (Fabro, Swift Current, Canada) was used to seed all plots 16 Apr 2024 with 23-cm row spacing. At Moccasin, a 1.5-m wide self-fabricated low-disturbance no-till disk seeder was used to seed all plots 4 Apr 2024 with 30-cm row spacing. Plot sizes were 1.8 by 7.5 m at Bozeman, and 1.5 m by 6.0 m at Moccasin. Seeding rates at Bozeman were 30, 200, and 80 live seeds per m² for *Bridger* chickpea, *Avondale* lentil, and *CDC Amarillo* yellow pea respectively. A higher seeding rate of 50 live seeds per m² for chickpea was used at Moccasin, where stand densities for this crop are known to fall consistently below targets. Live seeds were inoculated in-furrow at planting with *Exceed* granular inoculant (list company and place of manufacture) at a rate of 6.8 kg ha⁻¹. At Bozeman and Moccasin, a land roller of 61 cm in diameter and 470 kg/m of downward force was used.

Hand sampling of crop biomass occurred as soon as each pulse species reached physiological maturity (> 90% seed color turn). Two one-meter-long rows of above-ground biomass were cut flush with the soil surface by hand with a hand-held serrated sickle (Zenport, Sherwood, OR).

The hand-harvested area was measured by taking into account the row spacing of the crops rather than using a square-meter quadrant. Six plants were then randomly selected from each sample and morphology measurements taken. Each of the six plants were laid flat on the ground against a measuring tape where two measurements were recorded: total plant height and the height from the bottom of the plant stem to the first pod. Once morphology measurements were recorded, all harvested biomass samples were placed in cloth bags for storage. Once morphology measurements were recorded, all harvested biomass samples were placed in cloth bags within 24 hr of hand-sampling in a dryer at 50 °C for 72 hr, weighed and then mechanically threshed using a Wintersteiger A-4910 combine (Wintersteiger USA Salt Lake City, UT) for measured seed mass. Seed yield from the hand-sampled biomass from Moccasin was extremely immature due to premature harvest and associated hail damage, and therefore hand-harvested yield data was not included in this report. The entire pulse crop plots were later harvested with a conventional plot harvester.

Table 3-2: Summary of agronomic factors at Bozeman and Moccasin, MT, 2024.

Agronomic factors	Bozeman			Moccasin		
	Chickpea	Lentil	Pea	Chickpea	Lentil	Pea
Short Stubble Height (cm)	12			20		
Tall Stubble Height (cm)	45			55		
Cultivar	Bridger	Avondale	CDC Amarillo	Bridger	Avondale	CDC Amarillo
Row Spacing (cm)	23			30		
Plot size (m)	1.8 x 7.5			1.5 x 6.0		
Inoculant	Exceed Granular at 6.8 kg ha ⁻¹					
Seeding Rate (live seeds per m ²)	30	200	80	50	200	80
Planting dates	16 Apr			24 Apr		
Land Rolling Dates	20 May			12 June		
Applied Roller Force (kg/m)	470			470		
Biomass Hand Sampling Dates	7 Aug	22 July		7 Aug	23 July	
Machine Harvest Dates	21 Aug	2 Aug		3 Sep	13 Aug	

Statistical Analyses

This study was a randomized complete block design with a split-split plot arrangement, with stubble height (< 20 vs. > 45 cm) as the main plot factor, pulse species chickpea, lentil, pea as subplot factors, and rolling treatments (rolled vs. unrolled) as subsubplot factors. All treatments were replicated four times. Replication was included in the statistical model as a random effect while stubble height, pulse crops, and rolling treatments were treated as fixed effects using R version 4.4.2 (R Core Team, 2024) with base R packages. Interaction of crop species is not

included in this report as the variance dominated the model. For each response variable, analysis of variance (ANOVA) was conducted to evaluate main effects and interaction terms. Statistical significance was assessed at a threshold of $\alpha=0.05$. Where significant interaction effects were identified, post hoc analyses were conducted using Tukey–Kramer honest significant difference (HSD) comparisons to explore the combined influence of stubble height and rolling treatments on pulse crop performance. The statistical model used was:

$Y_{ijkl} = \mu + \text{rep}_i + \text{stubble}_j + (\text{rep} \times \text{stubble})_{ij} + \text{treatment}_k + (\text{stubble} \times \text{treatment})_{jk} + \varepsilon_{ijkl}$, where Y_{ijkl} represents the observed response variable, μ is the overall mean, rep_i is the effect of stubble height, $(\text{rep} \times \text{stubble})_{ij}$ is the interaction between replications and stubble height and serves as the error term to measure stubble effects, treatment_k is the effect rolling treatment, $(\text{stubble} \times \text{treatment})_{jk}$ is the interaction between stubble height and rolling treatment, and ε_{ijkl} is the error term.

Results and Discussion

Morphology

The most consistent responses to very tall stubble across all three pulse crops was an increase in the basal pod height (Table 3-4), with gains of 2.3, 3.0, and 3.2 cm in chickpea ($P=0.02$), lentil ($P<0.01$), and pea ($P=0.04$) at Bozeman, respectively. At Moccasin (Table 3-5), basal pod height was increased only for lentil, by 2.8 cm ($P=0.05$). Zhang et al. (2020) reported a shading effect via tall stubble contributed to soybean (*Glycine max L.*) internode elongation. Additionally, Cutforth et al. (2002) reported a trend of increased basal pod height among pulses across a three-year study when grown in tall cereal stubble due to a shading effect and increased stored soil-water. This elevation in pod height is agronomically important as it can increase cutting height and harvest efficiency, and potentially avoid costly repairs and equipment downtime. A common concern among pulse growers is harvestability because plants produce seed very close to the ground, and as a result, harvester headers must be set close to the ground to capture the basal pods (McVay et al. 2013).

Chickpea increased in plant height at Bozeman and Moccasin by 4.2 cm ($P=0.01$) and 2.6 cm ($P<0.01$), respectively, when grown in very tall stubble (Tables 3-4 and 3-5). Again, this suggests

an internode elongation due to the tall stubble's shading effect (Cutforth et al. 2007). It is also possible that these results suggest the microclimatic conditions provided by taller stubble, such as reduced wind exposure and moderated soil temperatures (Cutforth et al. 2002), may promote vertical growth among pulse species. No differences occurred for plant height due to stubble height for lentil. Pea was shorter at Moccasin ($P=0.02$) by 3.5 cm in tall stubble (Table 3-7). This result is counterintuitive as pea tendrils typically utilize tall stubble as a trellis to climb up and gain structural support from (Cutforth et al. 2007). Note that pea was heavily damaged by a hail event, perhaps confounding normal growth. Chickpea plant height increased with stubble height at Bozeman, pea plant height decreased at Moccasin, and there was no difference in lentil plant height at either location, suggesting a potential crop-specific response to stubble height.

Biomass and Yield

Chickpea biomass increased by 0.74 Mg ha^{-1} ($P=0.03$) when grown in tall stubble at Bozeman. Similarly, Cutforth et al. (2002) reported an increasing trend for chickpea biomass when grown in tall stubble. This trend was attributed to an increase in WUE, rising from $8.1 \text{ kg ha}^{-1} \text{ mm}^{-1}$ when grown in short stubble to $8.7 \text{ kg ha}^{-1} \text{ mm}^{-1}$ when grown in tall stubble. No stubble height effects were observed for biomass for lentil or pea at Bozeman, or for any of the three pulse species grown at Moccasin.

Both locations had an interaction effect between stubble height and rolling treatment for chickpea biomass. Biomass increased by 1.91 and 0.30 Mg ha^{-1} for the tall*rolled treatment compared to short*rolled treatments at Bozeman and Moccasin, respectively (Table 3-6). However, the absence of similar interactions in other crops or for other parameters indicates that this benefit may be context-dependent, or a random occurrence, highlighting the need for further investigation.

No differences in seed yield were observed for chickpea or pea at either location. Lentil yield increased 167 kg ha^{-1} ($P<0.01$) for tall vs short stubble at Bozeman. Cutforth et al. (2002) found that tall cereal stubble in semiarid Saskatchewan, reduced evaporation and wind speeds at the soil surface by 15% and 45%, and increased yields and WUE by 9% and 8% across pulses when compared to short stubble. No lentil yield differences due to treatments were observed at Moccasin. Prior research in the semiarid Canadian prairie showed that total water use did not

change based on stubble height, however yield and WUE increased with stubble height by 14% and 6%, respectively, indicating better protection of stored soil-water in tall stubble (Cutforth and McConkey 1997, Cutforth et al. 2002). It is important to note that in those studies, stubble height was left uniformly tall over the winter with shorter stubble heights attained in spring prior to seeding, thus their conclusions ignored potential differences in snow catch.

Circumstantial benefits of tall stubble were noted in semiarid Saskatchewan where tall stubble failed to provide agronomic benefits to spring-seeded crops under exceptionally wet and cool conditions, slowing the drying of the soil and delaying seeding (Cutforth et al. 2002).

At Bozeman, a decrease in lentil plant density (from 172 to 153 m⁻²) was observed in tall stubble. However, both these densities were above economic thresholds as reported by Bourgault et al. (2024). A winter pulse study nearby to Bozeman suggested that in instances of unusually cool weather, crops grown in a heat-limited environment may benefit from earlier soil-warming associated with shorter stubble (Chen et al. 2006). This result, however, was not seen across all study years, suggesting temperature and weather patterns play a role in stubble height's effect on seedling mortality.

Table 3-3: P-values from ANOVA for biomass, harvest index (HI), basal pod height, plant height, grain yield and plant density at Bozeman, MT.

Cultivar	Source of variance	df	Basal Pod Height	Biomass	HI	Machine Yield	Plant density	Plant Height
Chickpea								
	Stubble	1	0.02	0.03	0.49	0.56	0.72	0.01
	S x R	3	0.59	<0.01	0.32	0.44	0.94	0.44
Lentil								
	Stubble	1	<0.01	0.97	0.58	<0.01	0.04	0.60
	S x R	3	0.21	0.70	0.78	0.18	0.08	0.93
Pea								
	Stubble	1	0.04	0.15	0.61	0.18	0.43	0.11
	S x R	3	0.39	0.38	0.04	0.77	0.33	0.76

Table 3-4: Means of stubble height and on pulse crop performance across chickpea, lentil and pea at Bozeman, MT, 2024.

Cultivar	Stubble Height	Basal Pod Height	Biomass	HI	Machine Yield	Plant Height	Plant Density
		cm	Mg ha ⁻¹	kg ha ⁻¹ mm ⁻¹	kg ha ⁻¹	cm	Plants m ²
Chickpea	Short	25.0 b	4.44 b	0.510 a	2184 a	44.3 b	31.7 a
	Tall	27.3 a	5.18 a	0.457 a	2204 a	48.5 a	30.4 a
Lentil	Short	21.6 b	5.09 a	0.298 a	1516 b	42.0 a	174 b
	Tall	24.6 a	5.10 a	0.333 a	1683 a	41.2 a	153 a
Pea	Short	44.4 b	5.60 a	0.464 a	2532 a	52.0 a	65.4 a
	Tall	47.6 a	6.21 a	0.440 a	2660 a	55.7 a	61.0 a

Note: Mean values within a column and pulse crop sharing a letter are not significantly different ($p < 0.05$).

Table 3-5: Mean values of stubble treatment effects for all pulse crop species at Moccasin, MT, 2024

Cultivar	Source of Variation	Basal Pod Height	Biomass	HI	Machine Yield	Plant Height
		cm	Mg ha ⁻¹		Kg ha ⁻¹	cm
Chickpea						
	Short	25.2 a	1.54 a	0.364 a	1130 a	36.3 b
	Tall	27.3 a	1.61 a	0.353 a	1132 a	38.9 a
Lentil						
	Short	14.4 b	1.27 a	0.373 a	945 a	31.3 a
	Tall	17.2 a	1.16 a	0.408 a	906 a	31.8 a
Pea						
	Short	32.8 a	1.48 a	0.361 a	1066 a	44.9 a
	Tall	31.9 b	1.32 a	0.461 a	1069 a	41.4 b

Note: Mean values within a column and cultivar sharing a letter are not significantly different ($p < 0.05$).

Table 3-6: Tukey–Kramer honest significant difference (HSD) comparisons based on the interaction of stubble height and rolling treatment at Bozeman and Moccasin.

Measured variable	Location	Source of variation	Mean value	df	Letter Significance ^a
Chickpea Biomass			Mg ha ⁻¹		
	Bozeman				
		Short*Rolled	4.05	6	b
		Tall*Unrolled	4.66	6	ab
		Short*Unrolled	4.83	6	ab
		Tall*Rolled	5.96	6	a
	Moccasin				
		Short*Rolled	1.47	6	b
		Tall*Unrolled	1.48	6	ab
		Short*Unrolled	1.61	6	ab
		Tall*Rolled	1.74	6	a

Note: common letter display column denotes significant differences among comparisons via Tukey-Kramer HSD at the P = .05 level.

Overall, the results indicate a valuable response for increasing basal pod height of pulse crops grown in tall stubble, potentially benefiting harvest efficiency importantly. Additionally, chickpea exhibited a strong biomass response, increasing in tall stubble at Bozeman and increasing in a tall*rolled interaction at both locations. The reduction in plant density observed in lentil under tall stubble may warrants further investigation to optimize stubble management strategies for stand establishment. This study also highlights the limitations of a single year study, which is unable to capture the variability inherent in environmental conditions, such as weather patterns, which can significantly influence crop performance and treatment effects. Multi-year studies are key to validate trends and build a more robust understanding of the treatment effects and associated outcomes.

Conclusion

The results of this study highlight the effects of tall stubble and land rolling on pulse crop growth, biomass, and yield. Across chickpea, lentil and pea, an increase in basal pod height was the most consistent response to very tall stubble, likely due to a shading effect provided by taller stubble that promotes internode elongation. Chickpea also increased in plant height when grown in tall stubble. This increase is agronomically beneficial, as it can improve harvest efficiency by raising the lowest pod height above the soil surface. However, the response to tall stubble was not uniform across species or locations. While chickpea biomass increased in tall stubble at Bozeman, no biomass differences were observed for lentil or pea, indicating species-specific interactions with stubble height.

Yield responses to tall stubble were inconsistent, reinforcing the idea that environmental conditions and crop-specific traits play a role in determining agronomic benefits. While lentil yield at Bozeman increased in tall stubble, no yield differences were detected for chickpea or pea, nor for any crops at Moccasin. Prior research has shown that tall stubble can enhance water-use efficiency and yield in semiarid environments, but these benefits may not be universal, particularly under cooler and wetter spring conditions that could delay soil warming and crop establishment, such as occurred at both locations in 2024. Also, tall stubble integrity in the small-plot scenario was noted to be much less than in the field situation, due to a much higher proportion of trampling, perhaps indicating this is a difficult treatment effect to measure on a small-scale.

The decrease in lentil plant density in tall stubble at Bozeman further highlights the complexity of stubble height effects, potentially linked to temperature and moisture dynamics during early growth stages. Future research should further explore the interactions between stubble height, soil moisture, temperature fluctuations, and rolling operations to improve recommendations for optimizing pulse crop production based on stubble height and land rolling treatments.

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CHAPTER 4

BROADER IMPACT STATEMENT

The variability observed in pulse crop responses to tall cereal stubble across locations and species underscores the need for continued research on stubble height management in the NGP. As climate variability and drought intensifies across this semi-arid region, strategies that improve soil water conservation and enhance crop resilience are increasingly vital for sustaining productive agronomic systems. From this research, tall cereal stubble showed promising potential to increase soil moisture retention, reduce wind erosion, and improve pulse crop harvestability.

However, the inconsistency of results observed in this thesis highlights that a one-size-fits-all approach may not be effective. Crop rotations, year-to-year climate variability, and site-specific factors such as soil type, interact in complex ways that may influence pulse crop productivity and system sustainability. Without a deeper understanding of these interactions, positive outcomes of tall stubble in agronomic systems may not be fully realized by producers at field-scale.

Further research is needed to refine stubble height recommendations tailored to specific crop species, various climates, and management objectives across the diverse landscapes of the NGP. Multi-year trials at field-scale that can capture various precipitation amounts may help disentangle the effects of tall stubble on early crop establishment, soil water dynamics, and yields under variable climate scenarios. Advancing this knowledge will aid producers to make more informed decisions, balancing agronomic productivity with soil and water conservation goals. Ultimately, optimizing stubble management could play a pivotal role in strengthening the

resilience, profitability, and environmental sustainability of dryland cropping systems throughout the Northern Great Plains.

Additionally, after spending a considerable amount of time walking the field sites and observing their surroundings, it became clear that cereal stubble height influences the broader ecosystem far beyond its agronomic role. Throughout my observations, I consistently noted increased wildlife activity—upland birds, birds of prey, and ungulates—in areas with tall stubble compared to short or cultivated stubble. Tall stubble provides essential cover and shelter that short or cultivated stubble simply does not offer. This relationship between stubble height and wildlife habitat may attract interest from conservation organizations like Pheasants Forever, Quail Forever, and The Mule Deer Foundation, as much of the critical wildlife habitat in the Northern Great Plains overlaps with working agricultural lands. These organizations play a key role in bridging the gap between private landowners and the public by improving habitat, expanding access, and supporting research that benefits wildlife, landowners, and society alike.

Importantly, stubble height research has the potential to further expand public access to private lands across Montana through existing programs such as Block Management Area and Upland Game Bird Enhancement Program. These initiatives incentivize landowners—who are often directly involved in agriculture—to also serve as effective wildlife managers. From my experience, I have yet to meet a farmer or rancher who does not care about the health of the greater ecosystem on their property. Many are eager to engage in conservation programs that strengthen both the ecological integrity and long-term sustainability of the landscapes they depend on.

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APPENDICES

APPENDIX A

SENTEK RAINFALL EQUIVALENCE BY SENSOR

AVERAGED ACROSS ALL DEPTHS.

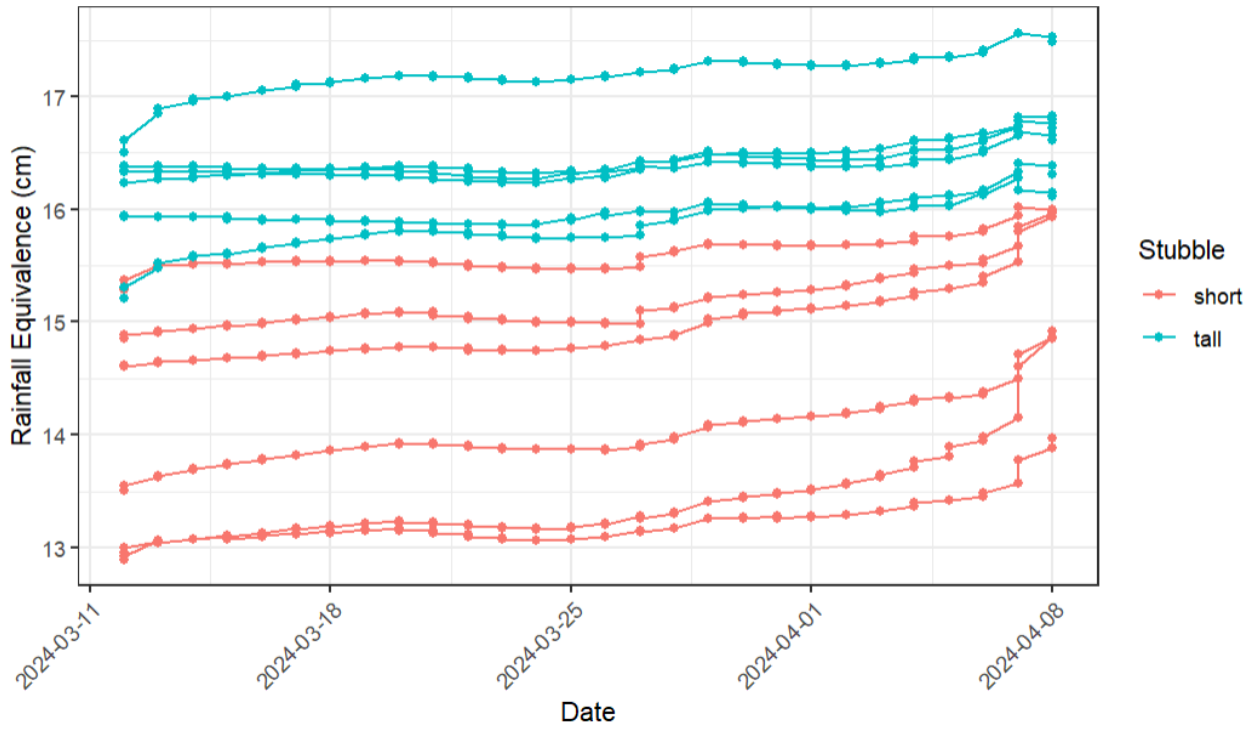


Figure A1: Time series plot of individual *Sentek* sensors by rainfall equivalence to a depth of 60 cm averaged across all depths from 12 Mar. to 8 Apr. 2025 at Geraldine, MT.

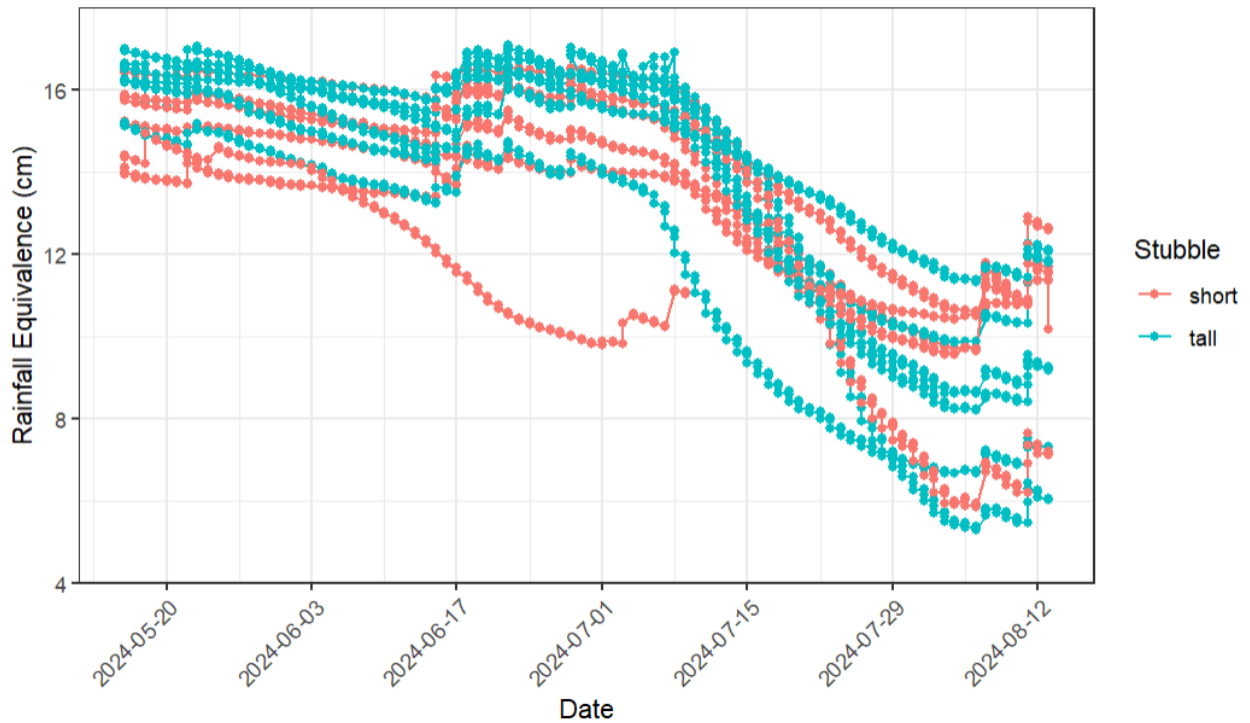


Figure A2: Time series plot of individual *Sentek* sensors by rainfall equivalence to a depth of 60 cm averaged across all depths from 16 May to 13 Aug. 2025 at Geraldine, MT.

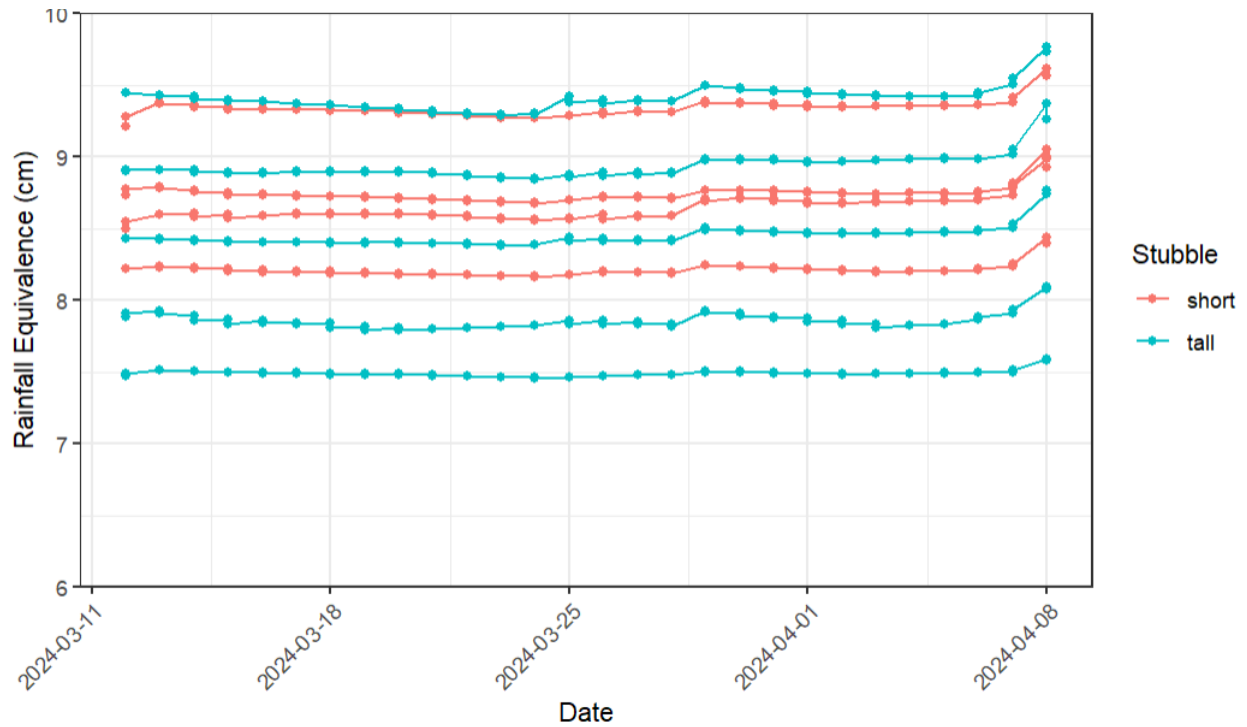


Figure A3: Time series plot of individual *Sentek* sensors by rainfall equivalence to a depth of 40 cm averaged across all depths from 12 Mar. to 8 Apr. 2025 at Moccasin, MT.

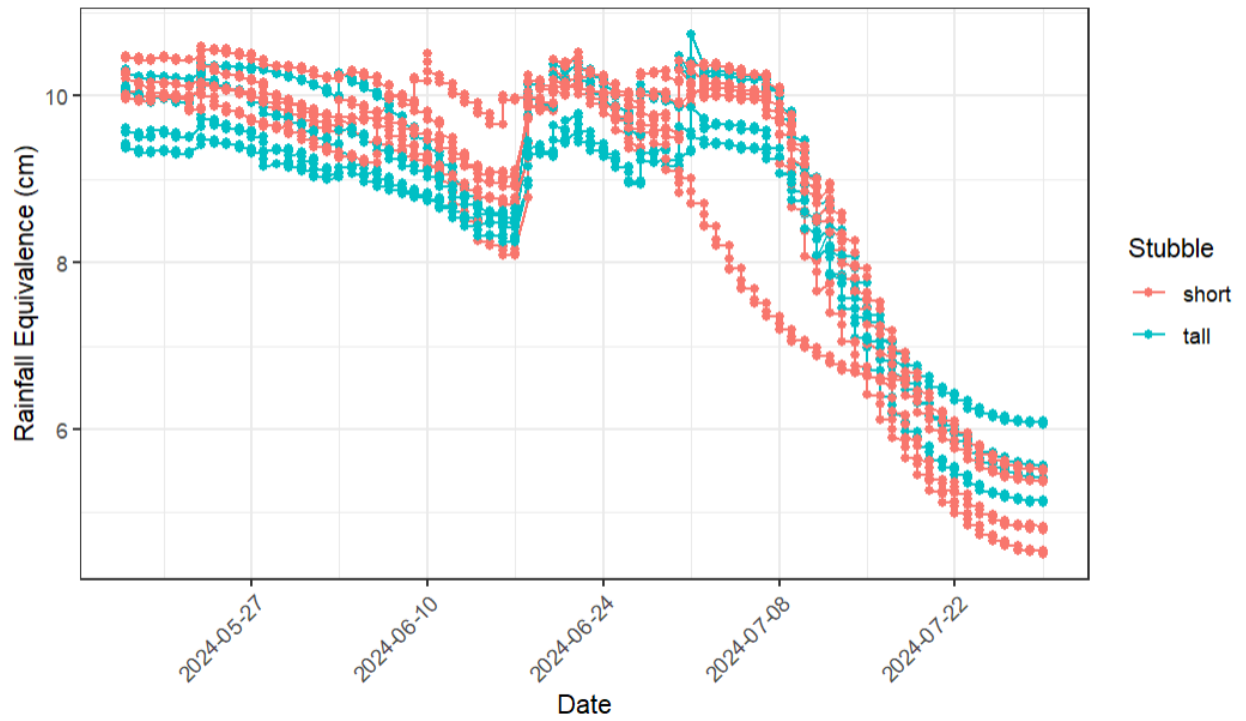


Figure A4: Time series plot of individual *Sentek* sensors by rainfall equivalence to a depth of 40 cm averaged across all depths from 16 May to 30 July, 2025 at Moccasin, MT.

APPENDIX B

SENTEK RAINFALL EQUIVALENCE BY DEPTH AVERAGED

ACROSS SENSORS

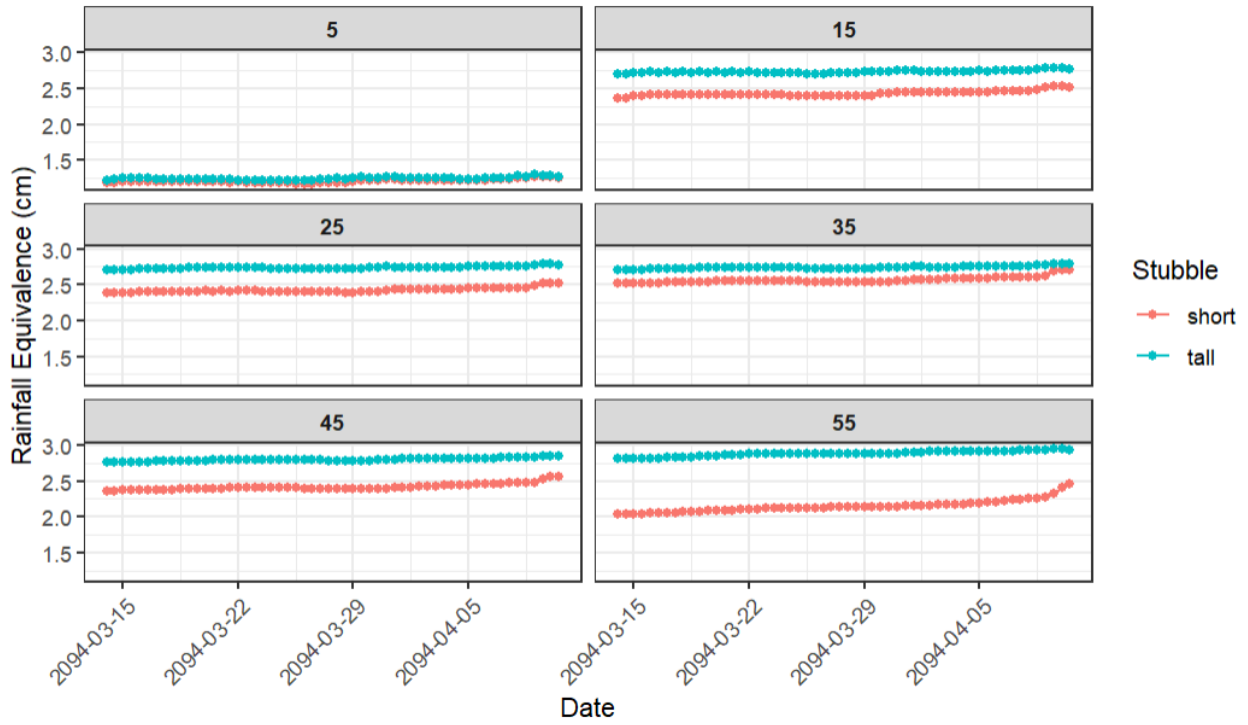


Figure B1: Time series plot of individual *Sentek* depths by rainfall equivalence to a depth of 55 cm averaged across all sensors from 12 Mar. to 8 Apr. 2025 at Geraldine, MT. Units for depth are in cm.

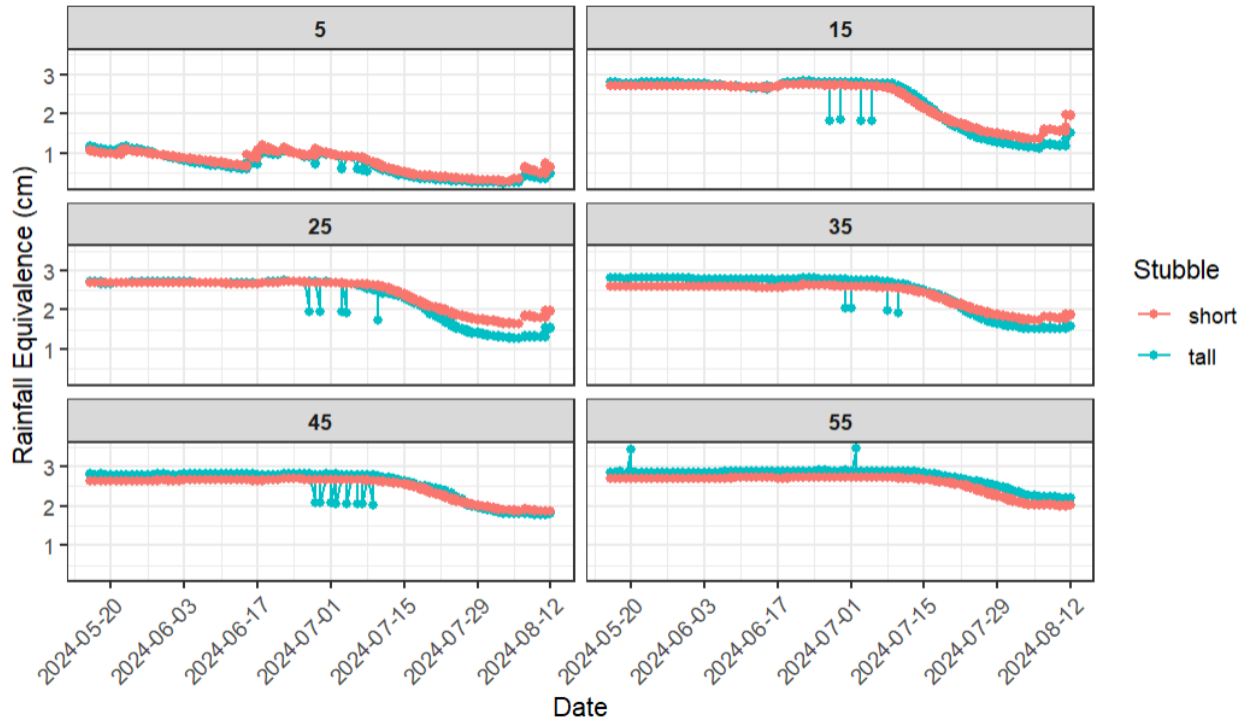


Figure B2: Time series plot of individual *Sentek* depths by rainfall equivalence to a depth of 55 cm averaged across all sensors from 16 May to 13 Aug. 2025 at Geraldine, MT. Units for depth are in cm.

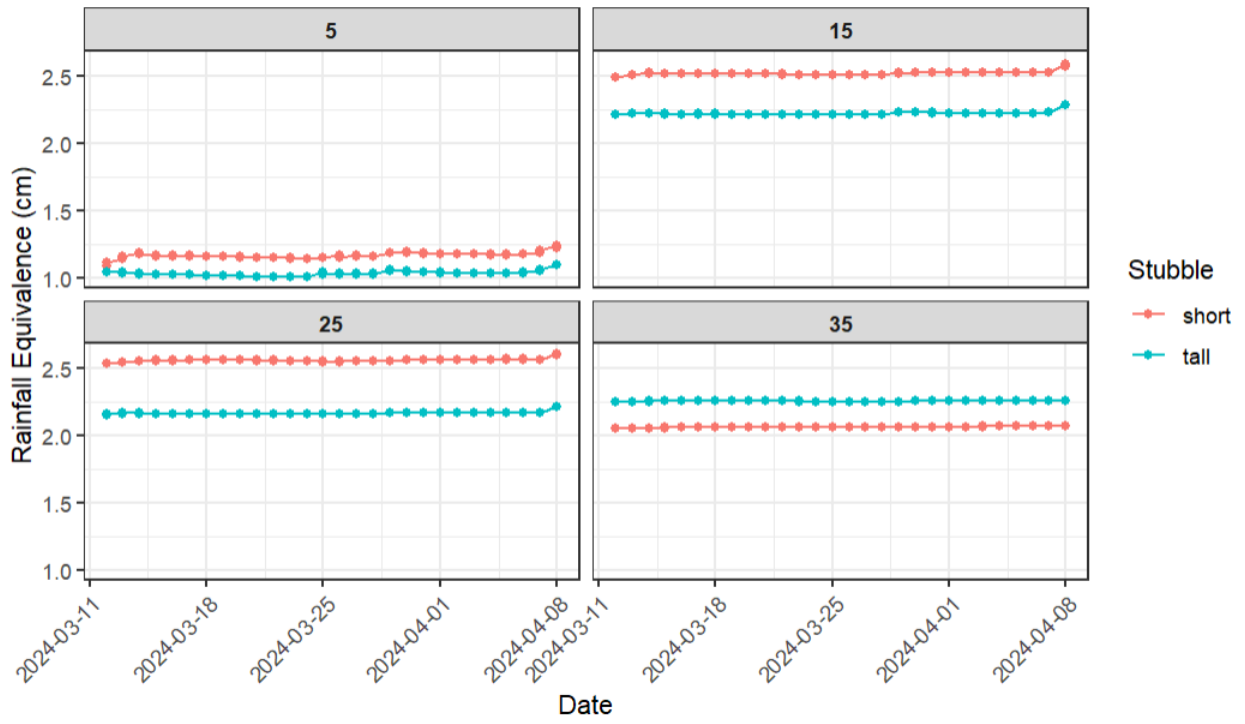


Figure B3: Time series plot of individual *Sentek* depths by rainfall equivalence to a depth of 35 cm averaged across all sensors from 12 Mar. to 8 Apr. 2025 at Moccasin, MT. Units for depth are in cm.

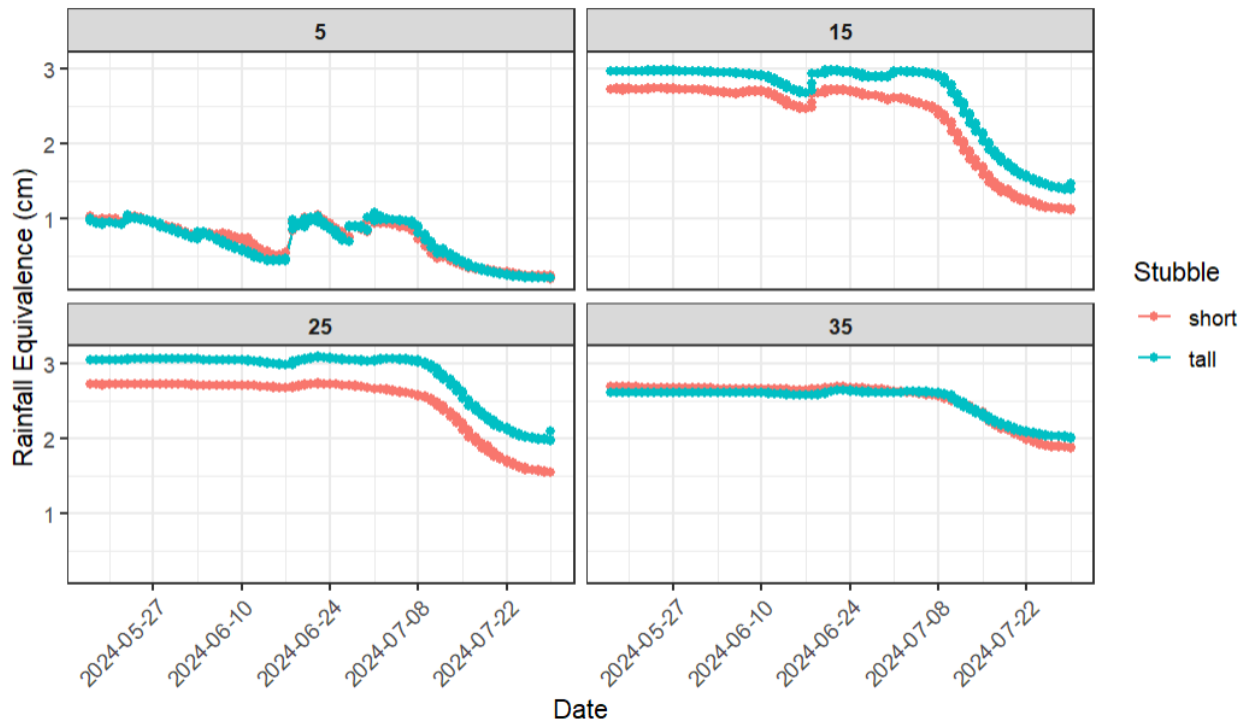


Figure B4: Time series plot of individual *Sentek* depths by rainfall equivalence to a depth of 35 cm averaged across all sensors from 16 May to 30 July, 2025 at Moccasin, MT. Units for depth are in cm.

APPENDIX C

SENSOR IDENTIFICATION BY LOCATION FOR EACH
FIELD SITE AND SEASON

Table C1: Sentek sensor location by season for each location with coordinates.

Location	Season	Stubble height	Sensor ID	Latitude	Longitude
Geraldine					
Winter					
		short	4446	47.68425	-110.22788
		short	4443	47.67957	-110.22777
		short	4724	47.68445	-110.22922
		short	4710	47.68162	-110.22806
		short	4714	47.68042	-110.22774
		short	4737	47.68107	-110.22822
		tall	4319	47.68463	-110.23432
		tall	4482	47.68412	-110.23443
		tall	4328	47.68242	-110.23251
		tall	4698	47.68188	-110.23250
		tall	4320	47.67913	-110.23437
		tall	4324	47.67910	-110.23485
Growing					
		short	4737	47.68425	-110.22788
		short	4324	47.67957	-110.22777
		short	4318	47.68445	-110.22922
		short	4328	47.68162	-110.22806
		short	4724	47.68042	-110.22774

Table C1 Continued.

	short	4482	47.68107	-110.22822
	tall	4446	47.68463	-110.23432
	tall	4710	47.68412	-110.23443
	tall	4698	47.68242	-110.23251
	tall	4313	47.68188	-110.23250
	tall	4323	47.67913	-110.23437
	tall	4714	47.67910	-110.23485
Moccasin				
Winter				
4317	short		47.07131	-109.90234
4329	short		47.07401	-109.90224
4318	tall		47.07145	-109.90107
4316	short		47.07168	-109.89988
4323	short		47.07276	-109.89979
4313	tall		47.07391	-109.89832
4325	tall		47.07489	-109.89825
4322	short		47.07484	-109.89712
4330	short		47.07192	-109.89716
4331	tall		47.07307	-109.89548
4332	tall		47.07429	-109.89569

Table 1 Continued.

Growing

4331	short	47.07131	-109.90234
4319	short	47.07401	-109.90224
4443	tall	47.07145	-109.90107
4330	short	47.07168	-109.89988
4325	short	47.07276	-109.89979
4322	tall	47.07391	-109.89832
4316	tall	47.07489	-109.89825
4332	short	47.07484	-109.89712
4320	short	47.07192	-109.89716
4329	tall	47.07307	-109.89548
4317	tall	47.07429	-109.89569
2832	tall	47.07369	-109.90108

APPENDIX D

STATEMENT OF DATA AVAILABILITY

All data presented in this thesis is made publicly available via Hydroshare (Barnes et al., 2025). Each research chapter (Chapters 2 and 3) contain their own folder comprised of three folders including code, data for analysis, and figures. The code folder contains coding language used to manipulate and compile the data as well as statistical models. Data for analysis folders includes all data necessary for the computation within the code folder. The figure folder contains all figures generated by the code.