COVER CROP EFFECTS ON WHEAT YIELD, NITROGEN USE EFFICIENCY, AND SOIL HEALTH IN A DRYLAND WHEAT SYSTEM

by

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GLOSSARY

ANUE agronomic nitrogen use efficiency

C:N carbon-to-nitrogen ratio

CC cover crop

DEWS drought early warning systems

EP effective precipitation

Kfs field-saturated hydraulic conductivity

LSD least significant difference

N nitrogen

NGP Northern Great Plains

PAW plant available water

RR: response ratio (%) = 100 × CC ÷ fallow

SARC Southern Agricultural Research Center

SD standard deviation

SE standard error

SIR substrate-induced respiration

SOM soil organic matter

SOC soil organic carbon

TC total carbon

TKW thousand kernel weight

WAS wet aggregate stability

ABSTRACT

Cover crops (CC) are increasingly adopted in dryland wheat systems, yet their agronomic and soil health impacts under semi-arid conditions with limited and variable precipitation remain poorly understood. This field trial at the Southern Agricultural Research Center in Huntley, Montana, evaluated six CC treatments and a fallow control, at four nitrogen (N) rates (0, 56, 112, and 168 kg N ha^{-1}), on spring wheat grain yield, grain protein concentration, agronomic nitrogen use efficiency (ANUE), and soil health indicators across five growing seasons.

Inter-annual weather variability was the dominant driver of all agronomic outcomes, substantially outweighing the influence of any management factor tested. Effective precipitation (EP) captured much of this variability; however, two years with nearly identical EP (2021 and 2024) produced notably different outcomes, indicating that precipitation timing or in-season distribution contributed to variation not fully explained by seasonal EP totals alone. Cover crop reduced wheat yield relative to fallow on average, although the magnitude depended on CC type and annual EP. N rate improved yield and protein with diminishing returns at higher rates, and ANUE was consistently lower under CC than under fallow when averaged across years and N rates. Grain protein responses were driven primarily by year and N rate, with wheat protein following pea averaging 7% higher than following fallow.

Soil health indicators showed limited responsiveness to CC management over the study period, with soil depth explaining more variation than CC treatment or N rate. Neither CC type nor N rate produced consistent improvements across the soil health metrics evaluated, except for aggregate stability.

These findings highlight a fundamental challenge for dryland producers: CC performance and N response are governed primarily by precipitation, a resource that is variable and difficult to predict. In environments where a single dry year can shift the agronomic and economic outcome of CC adoption, understanding how seasonal moisture mediates CC and N fertilization responses is essential. This study provides baseline evidence for that understanding in semi-arid Montana dryland systems.

CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Agriculture is one of the most important sectors of the global food system, underpinning food security for a growing world population. To meet rising demand for food, feed, and fiber, current agricultural practices rely heavily on synthetic external inputs, including fertilizers and pesticides, which, while increasing short-term productivity, can reduce long-term soil health and productivity (Kopittke et al., 2019). In response, sustainable agriculture has emerged as an approach that seeks to protect the environment while conserving and improving soil resources for future generations (Tilman et al., 2002). Within this framework, soil health has become a central focus, as healthy soils are fundamental to crop productivity and resilience under variable climate conditions.

Cover crops (CC) have gained broad recognition as a conservation practice capable of improving soil health, reducing erosion, and increasing long-term agricultural sustainability (Blanco-Canqui et al., 2015; Sharma et al., 2018). They are defined as close-growing crops planted to provide soil protection and improvement between periods of normal crop production (Soil Science Society of America, 2008). They are grown primarily to protect and enhance soil resources rather than for direct harvest, typically during the bare fallow period between two consecutive main crops, using residual soil nutrients, and are terminated before competition with the subsequent cash crop begins (Quintarelli et al., 2022). Numerous studies have reported that CC can improve soil health, slow erosion, suppress weeds, and limit nutrient losses through

leaching (Baraibar et al., 2018; Blanco-Canqui et al., 2013; De Baets et al., 2011; Koudahe et al., 2022; Lu et al., 2000; Nielsen et al., 2016; Poeplau and Don 2015).

Cover crops are also recognized as a management strategy that increases soil carbon inputs, enhances soil structure, and add organic biomass to the soil profile (Blanco-Canqui et al., 2013; Dabney et al., 2001; Jian et al., 2020; Nielsen et al., 2016; Poeplau and Don 2015). Furthermore, CC residues can moderate soil temperature, improve water infiltration, and reduce surface evaporation, thereby improving soil moisture retention (Alonso-Ayuso et al., 2014; Kaye and Quemada 2017).

Despite these documented benefits, CC effectiveness depends heavily on environmental conditions and management practices. Most evidence of positive outcomes comes from humid or irrigated regions, where water availability is less limited, and CC often improve soil quality without reducing cash crop yields (Blanco-Canqui et al., 2013; Poeplau & Don, 2015; Feng et al., 2023). Relatively few studies have examined CC adaptability in dryland agricultural systems, and their performance in semi-arid environments remains poorly understood and inconsistent (Choudhary et al., 2026; Unger and Vigil 1998; Feng et al., 2023). The effectiveness of CC is highly dependent on environmental conditions, and management approaches developed in more humid environments are often ill-suited to the climatic constraints of dryland systems (Unger & Vigil, 1998; Peterson et al., 2020; Choudhary et al., 2026). In water-limited systems, CC compete directly with cash crops for soil moisture (Unger and Vigil 1998). While CC may contribute to building soil health over time, they also extract water from the soil profile during their growth period. Consequently, CC adoption is generally more favorable in humid and subhumid regions where precipitation simultaneously supports soil improvement and crop production. In semi-arid regions, limited water availability increases the risk that potential soil health benefits from CC

may be offset by cash crop yield reductions, sometimes referred to as "yield penalties," making adoption less appealing to producers (Unger and Vigil 1998; Ghimire et al., 2018; Eash et al., 2021). Even small decreases in soil moisture in arid and semi-arid environments can meaningfully increase the risk of yield losses and crop failures (Unger and Vigil 1998).

The Great Plains of North America are among the largest semi-arid agro-ecosystems in the world, extending from the Canadian provinces of Alberta, Saskatchewan, and Manitoba south to Texas and New Mexico. The Rocky Mountains border the region to the west, and higher rainfall occurs in all areas to the east (Hansen et al., 2012). Annual precipitation generally ranges from 300 to 500 mm. Most precipitation falls during the April-to-July growing season and is characterized by high interannual variability (Padbury et al., 2002). Although irrigation is used in some areas, the Northern Great Plains (NGP) relies primarily on precipitation for crop production (Obour et al., 2021).

Wheat production in a dryland system is highly sensitive to environmental conditions, particularly drought, which can significantly reduce crop growth and yield (Mondal et al., 2015). To manage this water limitation, most Great Plains producers follow a cash crop–fallow rotation, with wheat as one of the dominant crops (Paulsen & Shroyer, 2008). Wheat is well-suited to the Great Plains because it can utilize stored soil moisture and, when planted early, matures before the hot, dry conditions of late summer (Hansen et al., 2012). Spring wheat was used in this study because fall soil moisture following CC may be insufficient for the reliable establishment of winter wheat.

Summer fallow periods are used to replenish soil moisture reserves for the next cash crop; however, while fallow can conserve soil moisture and reduce drought risk, long-term use of summer fallow degrades soil quality and organic matter, accelerates topsoil erosion, and limits

soil biological activity (Nielsen & Calderón, 2011; Zuazo & Pleguezuelo, 2009; Stewart, 2016; Hansen et al., 2012; Williams et al., 2022; Gilley et al., 2001). Despite their environmental drawbacks, wheat-fallow rotations remain common practice in the NGP (Carr et al., 2021).

Climate projections for Montana indicate that mean annual temperatures are expected to increase by 2.5 to 3.3°C by mid-century and as much as 5.6 to 6.7°C by the end of the century, with summer precipitation projected to decrease, particularly in the central and southern parts of the state (Whitlock et al., 2017; Conant et al., 2018). Many soils in the NGP have inherently low organic matter content and weak structural stability, which restricts their capacity to retain water and nutrients, making it increasingly difficult to maintain soil fertility and water availability for cash crops under projected future conditions (Hansen et al., 2012).

Given these projected conditions, cover crops have been proposed as a potential replacement for summer fallow to diversify rotations and improve soil health (Williams et al., 2022; Obour et al., 2021). In Montana and across the Northern Great Plains, summer fallow area has gradually declined in recent decades, reflecting a regional shift toward more intensive and diversified cropping practices (Carr et al., 2021). However, in the NGP's semi-arid dryland systems, CC performance is strongly influenced by water use, N dynamics, and legacy effects on the following wheat crop (Unger & Vigil, 1998; Lu et al., 2000; Stipešević & Kladivko, 2005; Thorup-Kristensen et al., 2003; Ghimire et al., 2019; Koudahe et al., 2022). Management approaches developed under more humid environments are often poorly aligned with local climatic conditions, which may limit their success when transferred to dryland systems. The risk of soil moisture depletion and yield penalties has constrained the widespread adoption of CC in the Great Plains. This study evaluates whether the potential soil and rotational benefits of cover crops can outweigh these costs in a dryland Montana system.

Results from across the Great Plains on CC effects on wheat yield have been inconsistent. Some studies report that CC reduced wheat yields primarily due to soil water depletion during the CC growth period, with higher CC biomass often reducing soil moisture at planting and increasing the risk of yield penalties compared with summer fallow (Unger & Vigil, 1998; Ghimire et al., 2019). Others found that legume CC or certain functional mixtures contributed N or structural benefits that partially or fully offset yield penalties (Nielsen & Vigil, 2010; Poeplau & Don, 2015). These contrasting findings underline the need for multi-year, location-specific research in the region. The objectives of this study were to quantify the rotational effects of CC treatments on spring wheat yield, ANUE, and grain protein; to determine how N rates and interannual variation in precipitation influenced these responses; and to evaluate whether CC improve long-term soil health in Montana's dryland environment.

Throughout this thesis, the effect of CC on the following cash crop is reported using two complementary metrics. The response ratio (RR) expresses CC performance as a percentage of fallow: RR (%) = 100 × (yield following CC ÷ yield following fallow). An RR of 100% indicates no difference from fallow, RR below 100% indicates a yield reduction following CC, and RR above 100% indicates a yield increase. The yield difference (YD) expresses the same comparison as a relative difference: YD (%) = 100 × (yield following CC − yield following fallow) ÷ yield following fallow. A YD of 0% indicates no difference from fallow; a negative YD is a yield penalty, and a positive YD is a yield gain. The two metrics are directly related by YD (%) = RR (%) − 100 (for example, RR = 79% is equivalent to YD = −21%, a 21% yield penalty, and RR = 113% is equivalent to YD = +13%, a 13% yield gain). RR is used in figures and tables so that values are bounded at a common reference of 100%, while YD is used in the text to describe the

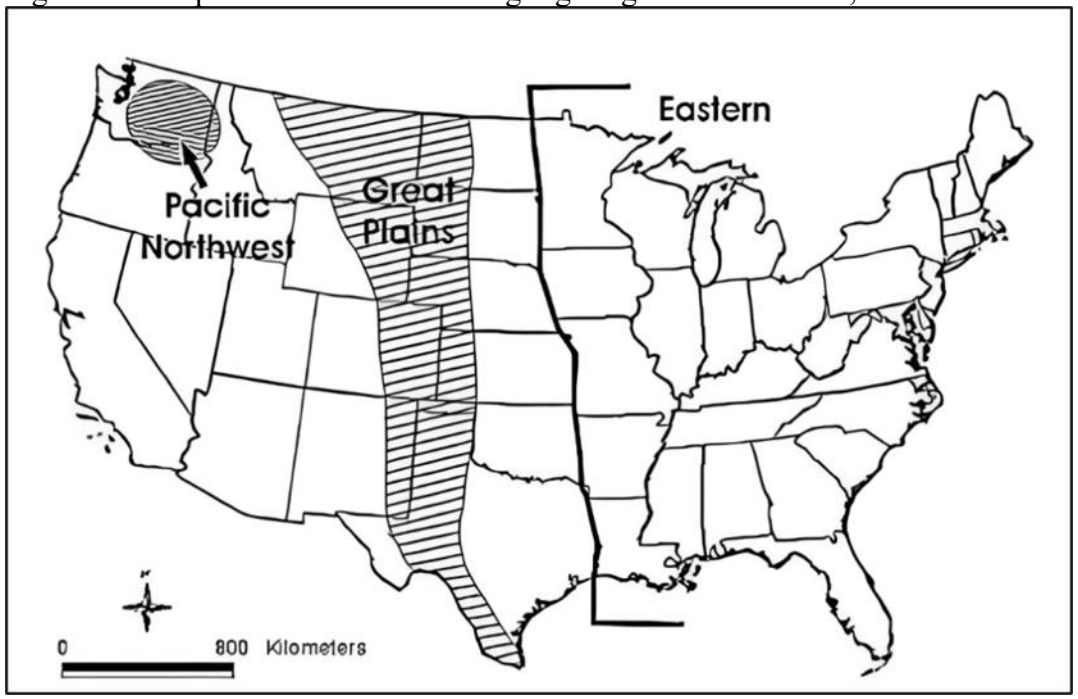
magnitude and direction of penalties and gains. Both are computed within site-year combinations and pooled across years or treatments where indicated.

The literature compiled in Tables 1.3 through 1.7 draws substantially on the organizational frameworks, study compilations, and categorization approaches of Blanco-Canqui and Jasa (2019) and Ruis et al. (2017), with additional studies identified from subsequent literature searches. Where the structure or scope of a table closely follows these sources, this is noted accordingly.

Table 1.1. Comparison of CC and fallow management systems in dryland cropping systems.

Aspect	**Fallow**	**Cover Crops**
Water	Conserve water for cash crop	May reduce water availability for the subsequent cash crop
Yield for cash crop	Generally higher and more stable in dry years	Can be reduced due to soil moisture depletion
Soil fertility	Mineralization of nutrients in the rest period	Add organic matter, and N fixation (legumes)
Soil erosion	Highly prone to erosion	Protect soil from erosion
Soil organic matter (SOM)	Often declines due to a lack of input	May increase SOM
Weed Control	Need herbicide (and/or multiple tillage passes)	Can reduce weeds by shading and competition
Economic Cost	Low cost	Higher seed, planting, and management costs
Long-term sustainability	Lower long-term sustainability	Can increase soil health and sustainability in the long term

Figure 1.1. Map of the United States highlighting the Great Plains, Pacific Northwest, and Eastern regions (Hansen et al., 2012).



1.2 Cover Crops in Dryland Agriculture

1.2.1 Challenges in dryland farming

Drylands cover approximately 67 million km², or about 45% of Earth's land surface (Huang et al., 2015; Prăvălie et al., 2019). Within this area, approximately 7.6 million km² (11% of drylands) is cropland and 20.2 million km² (30% of drylands) is pasture, with the remainder consisting of sparsely vegetated rangelands, shrublands, and deserts. Globally, drylands contain roughly 50% of all cropland and 74% of all pastures (Plaza et al., 2018; Fu et al., 2021). Despite their importance for food production, dryland systems are constrained by severe climatic and environmental limitations.

Among these limitations, water availability is the most critical factor affecting crop productivity. Because rainfall is often limited and highly variable, producers commonly adopt crop–fallow systems to conserve soil moisture. During summer fallow, fields remain unplanted for approximately 12 to 16 months to reduce the risk of crop failure and stabilize yields (O'Dea et al., 2013).

Across the semi-arid Great Plains and adjacent High Plains, field studies consistently show that chemical summer fallow leaves more plant-available water at wheat planting than CC. In Montana, an MSU Extension synthesis reported that cover-cropped fields typically end the fall with about 25 to 64 mm less soil water than summer fallow (Jones et al., 2022). Long-term experiments in Montana have shown that summer fallow can retain approximately 57 to 59 mm more soil water in the 0.6–0.9 m soil profile compared with cover crop mixtures (O'Dea et al., 2013). On-farm trials in Montana and studies from the Central Great Plains, including Akron, Colorado, report similar patterns of greater soil water under summer fallow than under CC

(Nielsen & Vigil, 2010). Soil water depletion has been shown to increase with CC biomass, with about 10 mm less water for every 1,000 kg ha^{-1} of biomass produced (Dhital & Raun, 2016). In dryland systems where total plant-available water in the profile typically ranges from 100 to 150 mm, a depletion of 25–50 mm under moderate CC biomass production represents a meaningful fraction of the water available to the subsequent cash crop.

Although summer fallow improves short-term soil water availability, its long-term use is linked with a decline in soil quality (Nielsen & Calderón, 2011; Tian et al., 2005; Hall et al., 2006). Repeated fallow cycles can limit carbon inputs, deplete organic matter, weaken soil structure and nutrient retention, leave the surface vulnerable to wind and water erosion, and suppress microbial activity, collectively threatening the long-term sustainability and productivity of dryland cropping systems.

In semi-arid regions such as the NGP, producers have historically relied on wheat as a staple crop because it is well-suited to the climate. Cover crop have been proposed to add biomass to the soil, and through legume species, to add N. However, their use introduces a critical tradeoff: the soil health benefits of CC come at the cost of reduced soil moisture available to the subsequent cash crop, which can reduce yields in dry years (DuPre, 2020).

Research shows that management decisions strongly influence this tradeoff, particularly the timing of CC planting, species selection, and termination timing (Blanco-Canqui et al., 2015). Early termination, such as at anthesis (flowering stage), is commonly recommended to conserve soil moisture for the subsequent cash crop (Miller et al., 2011).

1.2.2 Cover Crop Impacts on Wheat Yields

Cover crop impacts on cash crops vary widely depending on environmental conditions. Across all crop types, precipitation availability and trial duration are the two strongest predictors of CC impact on subsequent yield, with CC species becoming relevant only under higher precipitation conditions (Table 1.2). In the driest environments (annual precipitation < ~360 mm), yield differences were calculated as:

$$\frac{yield\ after\ CC\ -\ yield\ after\ fallow)}{yield\ after\ fallow} \times 100$$

These were severe and consistent regardless of CC species. Lenssen et al. (2007) reported penalties ranging from 53% (47% loss) for mustard to 70% (30% loss) for chickpea under annual precipitation levels of 77 to 246 mm over six years. Aiken et al., (2013) documented penalties of 31% (69% loss), 34% (66% loss), and 41% (59% loss) for sunflower, soybean, and spring canola, respectively, where annual precipitation was less than 358 mm over three years, while Miller et al., (2023) found a yield penalty of 44% (56% loss) for pea where annual precipitation remained under ~300 mm over eight years.

Under intermediate annual precipitation (360 to 500 mm), penalties persisted but were attenuated, with RR generally ranging from 68% to 91% across multiple site-years and species (Pikul et al., 1997; Lyon et al., 2004; Nielsen & Vigil, 2005; Ghimire et al., 2019; Miller et al., 2023). High interannual variability in precipitation within this range, rather than species choice, seemed to drive much of the variation in outcomes across sites (Miller et al., 2023), making CC performance difficult to reliably predict in this intermediate zone.

The RR clearly reversed when precipitation exceeded ~500 mm and trial duration exceeded five years. Under annual precipitation of ~870 mm over nine years, Chahal et al. (2020) found that oilseed radish(Raphanus sativus var. oleiformis), oat(Avena sativa), and rye (Secale cereale) produced small yield RR of 100% (no difference) to 106% (6% gain) relative to fallow. In another study with annual precipitation of ~560 mm over 15 years, Blanco-Canqui et al., (2012) documented RR of 133% (33% gain) for late-maturing soybean and 60% for sunn hemp (Crotalaria *juncea* L) ahead of sorghum, and RR of 113% (13% gain) and 131% (31% gain), respectively, for related treatments. The importance of trial duration is evident; shorter studies in similar precipitation ranges consistently showed neutral or negative responses, suggesting that soil health benefits from CC accumulate gradually before translating into yield gains. Chen et al. (2012) illustrated this transition, finding an RR of 102% (2% gain) for pea under 275 to 441 mm of annual precipitation over six years, an outcome that could have been negative in a shorter trial depending on precipitation conditions. Allen et al. (2011) similarly found only 85% (15% loss) for lentil in an environment where precipitation ranged from under 248 to 374 mm over 12 years, a substantially smaller penalty than shorter-duration studies at comparable precipitation levels, further supporting the role of trial length in attenuating negative effects.

Where precipitation was sufficient, legume yields outperformed grasses and brassicas. This pattern was most clearly demonstrated in maize systems, where Hunter et al. (2019) reported an RR of 89% (11% loss) for cereal rye and 105% (5% gain) for pea under identical conditions (precipitation of 1,020 mm over five years), likely reflecting an N contribution that partially offset moisture competition. In drier systems, this species-level advantage disappeared, as moisture limitations overrode any N benefit. For example, Lenssen et al. (2007) reported RR

values of −30.0% for chickpea (a legume) and −47.0% for mustard (a non-legume), indicating similarly large yield penalties relative to fallow across species.

Table 1.2. Effects of yield response on subsequent crop yield following CC compared with fallow, across dryland production systems. RR (%) = 100 x (post-CC yield ÷ post-fallow yield). The value of 100 indicates no difference from fallow.

Reference	Precip. (mm)	Dur. (yr)	Cover Crop	Post-fallow yield (kg/ha)	Post-CC yield (kg/ha)	RR (%)
Spring Wheat | median RR = 58%						
Lenssen et al., 2007	77–246	6	Mustard	1,000	530	53
Miller et al., 2006	262–364	2	Pea	2,630	1,480	56
Lenssen et al., 2007	77–246	6	Lentil	1,000	580	58
Lenssen et al., 2007	77–246	6	Pea	1,000	630	63
Lenssen et al., 2007	77–246	6	Chickpea	1,000	700	70
Wheat | median RR = 96%						
Aiken et al., 2013	~358	3	Sunflower	2,857	878	30
Aiken et al., 2013	~358	3	Soybean	2,857	981	34
Aiken et al., 2013	~358	3	Spring Canola	2,857	1,178	41
Miller et al., 2023	~300	8	Pea	1,690	750	44
Nielsen & Vigil 2005	165–496	6	Pea	3,923	2,639	67
Miller et al., 2023	~320	8	All	3,730	2,560	68

Table 1.2 continued

Reference	Precip. (mm)	Dur. (yr)	Cover Crop	Post-fallow yield (kg/ha)	Post-CC yield (kg/ha)	RR (%)
Miller et al., 2023	~300	8	All	2,120	1,510	71
Pikul Jr. et al., 1997	248–374	5	Lentil	2,820	2,040	72
Lyon et al., 2004	347–548	3	Oat + Pea	2,010	1,560	77
Miller et al., 2023	~320	8	All	2,970	2,310	78
Miller et al., 2023	~300	8	Pea	2,120	1,660	78
Miller et al., 2023	~450	8	All	5,860	4,830	82
Miller et al., 2023	~450	8	Pea	5,860	4,850	83
Miller et al., 2011	330–345	3	Spring Pea	2,300	1,940	84
Ghimire et al., 2019	470	2	Canola	4,939	4,201	85
Allen et al., 2011	248–374	12	Lentil	2,475	2,110	85
Miller et al., 2023	~320	8	Pea	2,970	2,570	86
Miller et al., 2023	~300	8	All	1,930	1,730	89
Miller et al., 2023	308–551	10	Pea	3,760	3,360	89
Miller et al., 2023	~320	8	Pea	3,730	3,390	90

Table 1.2 continued

Reference	Precip. (mm)	Dur. (yr)	Cover Crop	Post-fallow yield (kg/ha)	Post-CC yield (kg/ha)	RR (%)
Chahal et al., 2020	~869	9	Rye	7,640	7,030	92
Miller et al., 2023	~450	8	Pea	3,540	3,300	93
Ghimire et al., 2019	470	2	Oat	4,939	4,734	96
Ghimire et al., 2019	470	2	Pea + Oat	4,939	4,737	96
Ghimire et al., 2019	470	2	Pea	4,939	4,766	96
Burgess et al., 2014	~450	4	Pea	3,230	3,160	97
Miller et al., 2023	~350	8	All	2,780	2,730	98
Miller et al., 2023	~350	8	Pea	2,780	2,740	98
Chahal et al., 2020	~869	9	OSR + Rye	7,640	7,530	98
Miller et al., 2023	275–330	2	Pea	1,740	1,730	99
Miller et al., 2023	~350	8	All	1,860	1,860	100
Chahal et al., 2020	~869	9	OSR + Rye	3,990	4,000	100
Chahal et al., 2020	~869	9	Oat	3,990	4,020	100

Table.1.2 continued

Reference	Precip. (mm)	Dur. (yr)	Cover Crop	Post-fallow yield (kg/ha)	Post-CC yield (kg/ha)	RR (%)
Miller et al., 2023	~350	8	Pea	1,860	1,880	101
Miller et al., 2023	279–336	2	Pea	2,480	2,610	105
Chahal et al., 2020	~869	9	Oat	7,640	7,800	102
Chen et al., 2012	275–441	6	Pea	2,140	2,190	102
Chahal et al., 2020	~869	9	OSR	7,640	7,850	102
Chahal et al., 2020	~869	9	Rye	3,990	4,120	103
Miller et al., 2023	~450	8	All	3,540	3,680	104
Miller et al., 2023	~350	8	Pea	1,960	2,070	105
Chahal et al., 2020	~869	9	Radish	3,990	4,210	105
Miller et al., 2023	330–345	3	Winter Pea	2,300	2,420	105
Miller et al., 2023	~300	8	Pea	1,930	2,120	109
Miller et al., 2023	~350	8	All	1,960	2,150	109

Table1.2. continued

Reference	Precip. (mm)	Dur. (yr)	Cover Crop	Post-fallow yield (kg/ha)	Post-CC yield (kg/ha)	RR (%)
Blanco-Canqui et al., 2012	~560	15	Soybean	1,500	2,000	133
Blanco-Canqui et al., 2012	~560	15	Hemp	1,500	2,400	160
Sorghum | median RR = 121%						
Blanco-Canqui et al., 2012	~560	15	LMS Soybean	3,200	3,600	112
Blanco-Canqui et al., 2012	~560	15	Sunn Hemp	3,200	4,200	131
Corn (Maize) | median RR = 89%						
Adeyemi et al., 2020 a	~848	2	Wheat	8,700	7,600	87
Hunter et al., 2019	1,020	4	Cereal Rye	12,900	11,500	89

Hunter et al., 2019	1,020	4	Pea	12,900	13,500	104

1.2.3 Nitrogen Use Efficiency (NUE)

Nitrogen use efficiency (NUE) encompasses several related metrics, including agronomic, physiological, and recovery-based definitions, that differ across studies in their calculation and interpretation. Because the literature reviewed here spans multiple cropping systems and research objectives, studies report NUE using different methods; results are synthesized across these definitions in Table 1.5.

Cover crops generally showed a positive but variable effect on NUE, with responses strongly influenced by N rate and CC type. Improvements in NUE were most consistent at low-to-moderate N rates, whereas high N inputs reduced NUE regardless of CC presence. In multiple systems, NUE declined as N rates increased, even when CC were present, indicating a strong inverse relationship between N input and utilization.

The CC functional type played a key role in NUE. Legume CC consistently increased NUE, particularly at lower N levels, due to their contribution of biologically fixed N. Non-legume CC showed more variable responses, with some cases of reduced NUE, likely due to temporary N immobilization during residue decomposition. Mixed-species systems generally produced more stable, moderate improvements in NUE, suggesting a balance between N supply and retention.

Nitrogen timing also interacted with CC. Systems where N application was better synchronized with crop demand showed improved NUE, whereas early N application sometimes led to reduced efficiency, even with CC. This highlights that fertilizer timing can override the benefits of CC.

Responses were not uniform across all environments. Some systems showed no effect of CC on NUE, indicating that environmental conditions, crop type, and soil characteristics can limit the impact of CC. Overall, CC can improve NUE primarily under optimized N management, with

the strongest benefits observed in systems that use legumes or mixed species and moderate N inputs.

Table 1.5. Effects of cover crops on nitrogen use efficiency (NUE) across different environments, soils, and management practices. Abbreviations: NTCC = no tillage cover crops, CTCC = conventional tillage cover crops.

Reference	Precip. (mm)	Crop	Cover Crop	N Rate (kg N ha^{-1})	NUE Responses
Unspecified Soil					
Habbib et al., 2017	~675 ~675 ~675	Winter wheat Winter wheat Winter wheat	Mixed CC, NTCC vs CTCC Mixed CC, NTCC vs CTCC Mixed CC, NTCC vs CTCC	0 161 215	NUE is generally higher under NTCC; the effect varies by year Increase in NUE-related traits under NTCC Variable response depending on year
Silt Loam					
Adeyemi et al., 2020 b	~1,000 ~1,000 ~1,000 ~1,000	Corn Corn Corn Corn	Wheat Wheat Wheat Wheat	168 (planting) 168 (sidedress) 112 + 56 (split) 56 + 112 (split)	Decrease Increase Mixed Increase
Zablotowicz et al., 2011	~1,300	Cotton	Austrian winter pea	0	Increase

Table 1.5 continued

Reference	Precip. (mm)	Crop	Cover Crop	N Rate (kg N ha^{-1})	NUE Responses
	~1,300	Cotton	Austrian winter pea	67	Increase
	~1,300	Cotton	Austrian winter pea	134	No change
	~1,300	Cotton	Hairy vetch	0	Increase
	~1,300	Cotton	Hairy vetch	67	Increase
	~1,300	Cotton	Hairy vetch	134	No change
Loamy Sand					
Hubbard et al., 2013	~1,192	Sweet corn	Sunn hemp + crimson clover	0	Increase
	~1,192	Sweet corn	Sunn hemp + crimson clover	67	Increase
	~1,192	Sweet corn	Sunn hemp + crimson clover	133	Increase
	~1,192	Sweet corn	Sunn hemp + fallow	67–133	Increase
	~1,192	Sweet corn	Crimson clover only	67–133	Moderate increase
Clay Loam					
Kaye et al., 2019	~1,020	Maize	Austrian winter pea	Manure-based	Increase
	~1,020	Maize	Clover	Manure-based	Moderate increase
	~1,020	Maize	Rye	Manure-based	Decrease
	~1,020	Maize	Oat / Radish	Manure-based	Neutral / slight decrease
	~1,020	Maize	3–6 species mixtures	Manure-based	Moderate increase
Silty Clay Loam					

Table 1.5 continued

Reference	Precip. (mm)	Crop	Cover Crop	N Rate (kg N ha^{-1})	NUE Responses
Gabriel Pérez et al., 2016	~350 ~350	Maize Maize	Barley Vetch	130 130	No change No change
Sandy Clay Loam					
Qi et al., 2024	~595 ~595 ~595	Maize Maize Maize	Rapeseed Rye Mixed system	75–300 75–300 75–300	Increase (8.1%) Increase (2.9%) Decrease with higher N

1.3 Cover Crops and Soil Health

Keywords:

Mean Weight Diameter (MWD), Wet Aggregate Stability (WAS), Erodible Fraction (EF), Green Manure (GMS), Dry Aggregate Stability (DAS), Corn–Soybean (CS), Continuous Corn (CC), Winter Wheat (WW), Wheat Fallow (W-F), Wheat Legume (W-L), Continuous Wheat (CW), No-Tillage (NT), Conventional Tillage (CT), Minimum Tillage (MT), Silty Clay Loam (Sicl), Sandy Loam (SL), Sandy Clay Loam (SCL), Silty Loam (Sil), Clay Loam (CL), Plant Available Water (PAW).

Incorporating CC into a farming system offers a potential pathway to maintaining or improving cash-crop productivity. However, how CC influences soils remains a matter of debate (Peng et al., 2024). Globally, CC have been extensively studied for their ability to improve various soil health parameters. Cover crops are increasingly recognized as essential components of sustainable and regenerative agricultural systems, with benefits for soil health and productivity across a wide range of climates, particularly in temperate regions (Blanco-Canqui et al., 2015). Climate conditions, CC species, management practices, and the duration of adoption influence the magnitude and direction of these effects. In this review, we examine how a few soil health parameters change in the presence of CC.

1.3.1 Soil Organic Matter (SOM) and Total Carbon (TC)

Across all soil textures, CC effects on SOC compared to summer fallow showed a general trend toward modest increases, though with substantial variability across studies and environments (Table 1.3). This apparent positive trend was largely driven by studies conducted under higher precipitation; in semi-arid environments receiving less than approximately 450 mm annual precipitation, SOC responses were consistently near-neutral regardless of CC species or trial duration. Responses across the full dataset depend on a combination of precipitation, soil texture, CC species, and trial duration rather than any single factor.

In coarser sandy loam soils, SOC responses to CC were highly variable and generally precipitation dependent. Under drier conditions, Ghimire et al. (2019) reported near-neutral SOC responses at approximately 470 mm annual precipitation, with RR values of 97% (3% loss) for a 6-species mix and 101% (1% gain) for oat. At intermediate precipitation, Sainju et al. (2018) observed RR values of 98% (2% loss) for rye and 98% (2% loss) for rye and vetch mixtures, but 104% (4% gain) for hairy vetch under approximately 1,140 mm annual precipitation. In contrast, Mpeketula and Snapp (2019) reported an RR of 92% (8% loss) under approximately 900 mm despite 20 years of CC management, indicating that long duration alone does not guarantee SOC gains. The strongest positive responses in this texture class occurred under the highest precipitation, where Hubbard et al. (2013) reported an RR of 132% (32% gain) for both sunn hemp and crimson clover under approximately 1,192 mm annual precipitation over five years.

In finer, drier silt loam soils receiving less than 600 mm annual precipitation, SOC responses were variable and strongly precipitation dependent. Blanco-Canqui et al. (2013) reported RR values ranging from 103% (3% gain) for winter lentil to 128% (28% gain) for spring triticale under approximately 489 mm, suggesting cereal species may accumulate SOC more effectively than legumes in this soil texture. At lower precipitation, however, Engel et al.

(2017) and Simon et al. (2022) found near-neutral RR values of 100% (no difference) and 105% (5% gain), respectively, at 411–450 mm annual precipitation, both statistically indistinguishable from fallow, suggesting that below approximately 450 mm, CC biomass production is too limited to drive meaningful SOC gains regardless of trial duration. Not all grass species produced positive outcomes at intermediate precipitation; Sindelar et al. (2019) reported an RR of 96% (4% loss) for winter rye under annual precipitation of approximately 655 mm. In finer, wetter silt loam soils receiving more than 600 mm annual precipitation, SOC responses were generally positive; Villamil et al. (2006) observed RR values of 103% (3% gain) for rye, 108% (8% gain) for vetch, and 111% (11% gain) for a rye and vetch mixture under annual precipitation of approximately 1,033 mm, while Zablotowicz et al. (2011) reported an RR of 141% (41% gain) for both Austrian winter pea and hairy vetch where annual precipitation was 1,300 mm ahead of cotton.

In the finest-textured soils, SOC responses were consistently neutral to positive regardless of precipitation. Blanco-Canqui and Jasa (2019) provided a clear within-study comparison in silty clay loam soils: leguminous CC produced no change in SOC (RR = 100%, no difference), whereas grass CC increased SOC to an RR of 111% (11% gain) under identical conditions of 693 mm annual precipitation over 12 years. Data for loam and clay loam soils were limited to one or two studies each and were insufficient to establish broader trends, though available data suggested modest positive responses with median RR values of 109% (9% gain) and 114% (14% gain), respectively.

Overall, grass CC tended to produce SOC gains equal to or greater than those observed with legume CC across soil textures (Blanco-Canqui et al., 2013; Blanco-Canqui & Jasa, 2019; Sainju et al., 2018). Precipitation emerged as the dominant moderating factor, with studies where

annual precipitation was below 450 mm consistently showing near-neutral responses and studies where annual precipitation was above 600 mm showing the strongest gains. However, substantial variability across studies limited firm conclusions, and longer-term controlled comparisons are needed to develop reliable SOC management recommendations for dryland systems.

Table 1.3. Effects of CC on soil organic carbon (SOC) and soil organic matter (SOM) across different environments, soil texture, and management practices. Response ratios (RR; 100 x SOC following CC / SOC following fallow) within a soil textural class are sorted by the study's mean annual precipitation.

Reference	Precip. (mm)	Dur (yr)	Depth (cm)	Cover Crop	System	SOC No-CC	SOC CC	RR%
Sandy Loam | median RR = 98%								
Ghimire et al., 2019	470	3	0–15	6-species mix	Wheat–sorghum	13.8	13.5	98
Ghimire et al., 2019	470	3	0–15	Oat	W–F	13.8	14	101
Mpeketula & Snapp 2019	900	20	0–15	Mixed CC	C–S, WW	9.3	8.6	92
Sainju et al., 2018	1,140	5	0–30	Rye	Sweet sorghum (bioenergy)	7.69	7.6	98
Sainju et al., 2018	1,140	5	0–30	Hairy vetch	Sweet sorghum (bioenergy)	7.69	8.04	104
Sainju et al., 2018	1,140	5	0–30	Vetch + rye	Sweet sorghum (bioenergy)	7.69	7.59	98

Table 1.3 continued

Reference	Precip. (mm)	Dur (yr)	Depth (cm)	Cover Crop	System	SOC No-CC	SOC CC	RR%
Hubbard et al., 2013	~1,192	4	0–15	Sunn hemp / Crimson clover	Sweet corn	5.5	7.3	132
Silt Loam | median RR = 109%								
Jones et al., 2025	358	7	0–10	Pea / Full 8-spp mix	CC–wheat (Amsterdam, MT semiarid)	12.5	13.5	108
Blanco-Canqui et al., 2013	~489	5	0–15	Winter lentil	W–F	10.9	11.3	103
Blanco-Canqui et al., 2013	~489	5	0–15	Spring pea	W–F	10.9	12.5	115
Blanco-Canqui et al., 2013	~489	5	0–15	Spring lentil	W–F	10.9	13.3	122
Blanco-Canqui et al., 2013	~489	5	0–15	Winter triticale	W–F	10.9	13.4	123
Blanco-Canqui et al., 2013	~489	5	0–15	Spring triticale	W–F	10.9	14	128

Table 1.3 continued

Reference	Precip. (mm)	Dur (yr)	Depth (cm)	Cover Crop	System	SOC No-CC	SOC CC	RR%
Sindelar et al., 2019	655	6	0–15	Winter rye	CC system	24.1	23.2	96
Rorick & Kladivko 2017	900	4	0–15	Cereal rye	C–S	14	15	107
Villamil et al., 2006	~1,033	5	0–30	Rye	C–S no-till	20.3	20.9	103
Villamil et al., 2006	~1,033	5	0–30	Vetch	C–S no-till	20.3	22	108
Villamil et al., 2006	~1,033	5	0–30	Vetch + rye	C–S no-till	20.3	22.6	111
Zablotowicz et al., 2011	~1,300	3	0–15	Austrian winter pea / Hairy vetch	Cotton	10.5	14.8	141
Engel et al., 2017	411	10	0–30	Pea grain	Pea–W (NT)	35.1 Mg ha^{-1}	34.9 Mg ha^{-1}	99
Simon et al., 2022	~450	~11	0–15	Oat/triticale/pea mix (standing)	W–sorghum–F	9.36	9.8	104
Clay Loam | median RR = 114%								

Table 1.3 continued

Reference	Precip. (mm)	Dur (yr)	Depth (cm)	Cover Crop	System	SOC No-CC	SOC CC	RR%
Jones et al., 2025	303	7	0–10	Pea / Full 8-spp mix	CC–wheat (Conrad, MT — semiarid)	10.7	12.2	114
Silty Clay Loam | median RR = 108%								
Blanco-Canqui & Jasa 2019	693	12	0–15	Austrian winter pea / Soybean	C–S, WW	49.3	49.3	100
Blanco-Canqui & Jasa 2019	693	12	0–15	Cereal rye / Grain sorghum	C–S, WW	49.3	54.9	111
Liu et al., 2005	~1,160	1	0–15	Annual ryegrass	Vegetables	17.5	19	108
Loam | median RR = 109%								
Antosh et al., 2020	250–300 + irrig.	2	0–20	Hairy vetch	Sweet corn (Leyendecker)	12.2	13.3	109
Blanco-Canqui & Jasa 2019	693	12	0–15	Soybean	C–S, WW	49.3	49.3	100

Table 1.3 continued

Reference	Precip. (mm)	Dur (yr)	Depth (cm)	Cover Crop	System	SOC No-CC	SOC CC	RR%
Blanco-Canqui & Jasa 2019	693	12	0–15	Cereal rye	C–S, WW	49.3	54.9	111
Blanco-Canqui & Jasa 2019	693	12	0–15	Grain sorghum	C–S, WW	49.3	54.9	111
Liu et al., 2005	~1,160	1	0–15	Annual ryegrass	Vegetables	17.5	19	108

1.3.2 Substrate-induced respiration, soil microbes

Substrate-induced respiration (SIR) is a widely applied method to estimate microbial biomass and activity by measuring respiratory response following the addition of a readily available carbon source (Anderson & Domsch, 1978). This approach typically uses glucose or yeast as substrates, with respiration measured either through chemical CO_2 trapping (e.g., NaOH titration) or through use of an infrared gas analyzer.

Soil type strongly influences microbial respiration (Table 1.4). Organic soils consistently show higher activity than mineral soils, and disturbed or tilled soils exhibit the lowest respiration (Hartley et al., 2009; Anderson & Domsch, 1978). In Oklahoma grassland soils respired approximately twice as high as in tilled soils (Gyawali et al., 2019), while biologically rich Chernozem soils in Russia showed greater activity than tundra and grey forest soils (Ananyeva et al., 2011). Anderson and Domsch (1978) similarly reported several-fold higher respiration and microbial biomass carbon in organic compared with mineral soils.

Management practices further modified these patterns. Generally, CC increased soil respiration relative to summer fallow in systems studied in Japan, the United States (Oregon), Spain, and the United Kingdom (Mendes et al., 1999; Nakamoto et al., 2012; Centurión et al., 2022; Adekanmbi et al., 2025), although the magnitude of responses varied with species and conditions. Differences in measurement methods, including yeast-SIR, glucose-SIR, and fumigation–incubation, resulted in variation in absolute values, but relative trends remained consistent across studies (Mendes et al., 1999; Hartley et al., 2009). Overall, soil respiration serves as a sensitive indicator of both inherent soil properties and management effects.

Table 1.4. Soil respiration rates and microbial activity indicators across soil textures, as well as measurement methods

Source	Method	Soil / Context	Incubation	Respiration rate (µg CO_2–C g^{-1} h^{-1})
Hartley et al., 2009	Yeast-SIR	Mineral & organic soils	~4 h	1–5 (mineral); 4–10 (organic)
Gyawali et al., 2019	Yeast-SIR	Grass vs tilled soil	4 h	~0.19 (grass); ~0.09 (tilled)
Ananyeva et al., 2011	Glucose-SIR	Chernozem, forest, tundra soils	5 h	0.2–5 (soil dependent)
Anderson and Domsch 1978	Yeast/Glucose-SIR	Agricultural soils	1–3 h (22 °C)	3.5–20 (mineral); 20–65 (organic)
Nakamoto et al., 2012	Glucose-SIR	Andosol & Fluvisol; CC vs fallow	4 h (22 °C)	0.3–1.2 (CC); 0.2–0.5 (fallow)

Table 1.4 continued

Source	**Method**	**Soil / Context**	**Incubation**	**Respiration rate (µg CO_2–C g^{-1} h^{-1})**
Mendes et al., 1999	Fumigation–incubation	Silt loam; CC vs fallow	10 d (25 °C)	1–1.4 (CC); 0.6–0.8 (fallow)
Centurión et al., 2022	Glucose-SIR	Mollisol; CC mixtures vs fallow	4 h (22 °C)	~0.93–1.67 (treatments); fallow ~1.52
Adekanmbi et al., 2025	SIR (plant substrate)	CC mixtures vs no CC	4 h (22 °C)	2.5–6 (CC); 2 – 3 (no CC)

1.3.3 Aggregate stability

Aggregate stability responses across soil textures, precipitation regimes, and management systems are summarized in Table 1.6. Across studies, CC generally improved aggregate stability, but the magnitude and consistency of response depended strongly on soil texture, precipitation, and management. In semi-arid Canadian prairie soils (annual precipitation of ~350 mm), legume green manures increased WAS from a baseline of 24.0% to 30.5–34.1% (RR = 127–142%, i.e., 27–42% gain; Biederbeck et al., 1998), with smaller increases (RR = 107–120%, i.e., 7–20% gain) observed in low-OM Saskatchewan soils depending on wetting method (Campbell et al., 1993). In humid silty clay loam (annual precipitation of 693 mm), grass CC increased large macroaggregate WSA from 12% to 22% (RR = 183%, 83% gain), while legume CC had no significant effect (Blanco-Canqui & Jasa, 2019). In a 34-year cotton system (1,350 mm annual precipitation), both CC types increased WAS modestly but not significantly (RR = 104–112%, 4–12% gain; Nouri et al., 2019).

In silty clay loam, late-terminated grass CC increased MWD from 1.34 to 1.70 mm (RR = 127%, 27% gain), while 100% residue removal reduced it to 1.03 mm (RR = 77%, 23% loss), highlighting the importance of residue retention (Ruis et al., 2017). Grass CC also increased MWD from ~1.85 to ~2.48 mm (RR = 134%, 34% gain) over 12 years, while legume CC had no effect (Blanco-Canqui & Jasa, 2019). In semi-arid silt loam (300–500 mm annual precipitation), grass CC raised MWD from ~0.50 to ~0.85 mm (RR = 170%, 70% gain) and spring legumes to ~0.75 mm (RR = 150%, 50% gain); winter lentil had no effect (Blanco-Canqui et al., 2013). Under wetter conditions (900 mm annual precipitation), grass CC increased MWD (RR = 155%, 55% gain at 0–10 cm and RR = 129%, 29% gain at 10–20 cm; Rorick & Kladivko, 2017). In clay loam (355 mm annual precipitation), diverse legume and brassica rotations increased MWD

from 10.67 to 19.31 mm (RR = 115–120%, 15–20% gain; Malhi et al., 2009). Short-term mixed CC trials (3–5 years) showed no significant MWD or WAS response, while 20-year mixed CC increased MWD (RR = 118–128%, 18–28% gain; Ball-Coelho et al., 2000; Mpeketula & Snapp, 2019).

Overall, grass CC produced the largest and most consistent MWD improvements in humid systems, while legume CC effects on WSA were most reliable in semi-arid, low-OM soils. Both metrics responded more strongly under longer management duration and adequate residue retention.

Table 1.6. Effects of CC and green manures on soil aggregate stability (WSA, MWD) across diverse climates, soils, and management systems.
Abbreviations: MWD = mean weight diameter; DAS = dry aggregate stability; GM = green manure; W–F = wheat–fallow; W–L = wheat–legume; GM–W = green manure–wheat; CC = cover crop; NT = no-tillage; OM = organic matter; C–S = corn–soybean; CSW = corn–soybean–wheat.

Reference	**Precip. (mm)**	**Dur. (yr)**	**System**	**CC Type**	**Metric**	**No-CC**	**CC**	**RR (%)**
Silty Clay Loam								
Blanco-Canqui & Jasa 2019	693	12	C–S, WW	Grass CC (rye, sorghum)	WSA 4.75–8.0 mm (%)	12	22	183
Blanco-Canqui & Jasa 2019	693	12	C–S, WW	Legume CC (winter pea, soybean)	WSA 4.75–8.0 mm (%)	12	14	117
Blanco-Canqui & Jasa 2019	693	12	C–S, WW	Grass CC (rye, sorghum)	MWD (mm)	1.85	2.48	134
Blanco-Canqui & Jasa 2019	693	12	C–S, WW	Legume CC (winter pea, soybean)	MWD (mm)	1.85	1.85	100

Table 1.6 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR (%)
Ruis et al. 2017	860/655	3	Continuous corn	Grass late termination (winter rye)	MWD (mm)	1.34	1.70	127
Ruis et al. 2017	860/655	3	Continuous corn	Grass (winter rye)	MWD (mm)	1.34	1.34	100
Ruis et al., 2017	860/655	3	Continuous corn	Grass 100% residue removal	MWD (mm)	1.34	1.03	77
Silt Loam								
Blanco-Canqui et al., 2013	300–500	5	W–F	Grass (winter/spring triticale)	MWD (mm)	0.50	0.85	170

Table 1.6 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR (%)
Blanco-Canqui et al., 2013	300–500	5	W–F	Legume (spring pea/lentil)	MWD (mm)	0.5	0.75	150
Blanco-Canqui et al., 2013	300–500	5	W–F	Legume (winter lentil)	MWD (mm)	0.50	0.50	100
Biederbeck et al., 1998	350	6	W–L	Legume (feedpea)	WAS (%)	24.0	30.5	127
Biederbeck et al., 1998	350	6	W–L	Legume (chickling vetch)	WAS (%)	24.0	31.0	129

Table 1.6 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR (%)
Biederbeck et al., 1998	350	6	GM–W	Legume (black lentil GM)	WAS (%)	24.0	34.1	142
Biederbeck et al., 1998	350	6	GM–W	Legume (Tangier flatpea GM)	WAS (%)	24.0	32.0	133
Sindelar et al., 2019	655	6	Irrigated corn	Grass (winter rye) CC effect	MWD 0–5 cm (mm)	2.1	2.1	100
Rorick & Kladivko 2017	900	4	C–S	Grass (cereal rye)	MWD 0–10 cm (mm)	2.3	3.6	155
Rorick & Kladivko 2017	900	4	C–S	Grass (cereal rye)	MWD 10–20 cm (mm)	2.0	2.6	129
Nouri et al., 2019	1,350	34	Cotton	Legume (hairy vetch)	MWD dry (mm)	2.48	3.01	121
Nouri et al., 2019	1,350	34	Cotton	Grass (winter wheat CC)	MWD dry (mm)	2.48	3.03	122

Table 1.6 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR (%)
Nouri et al., 2019	1,350	34	Cotton	Legume (hairy vetch)	WAS (%)	52.9	59.4	112
Nouri et al., 2019	1,350	34	Cotton	Grass (winter wheat CC)	WAS (%)	52.9	54.8	104
Sandy Loam								
Mpeketula & Snapp 2019	900	20	C–S, WW	Mixed (clover + rye)	MWD 0–5 cm (mm)	0.51–0.58	0.60–0.74	118–128
Ball-Coelho et al., 2000	900	3-5	Corn, wheat	Mixed (oat + radish)	WAS (%)	38.6	41.5 (ns)	108
Ball-Coelho et al., 2000	900	20	CC, CS, CSWco	Grass/mixed (winter CC)	MWD (mm)	38.6	38.6	>100
Indian Head (low OM) / Melfort (high OM)/Swift current/Scott								

Table 1.6 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR (%)
Campbell et al., 1993a	427	34	Indian Head, low OM	sweet clover	WAS fast-wet	38.6	53.4	138
Campbell et al., 1993a	427	34	Indian Head,	alfalfa-bromegrass	WAS fast-wet	38.6	71.8–76.8	186–199
Campbell et al., 1993a	410	34	Melfort, high OM	sweet clover	WAS fast-wet	45.7	50.6	111
Campbell et al., 1993a	410	34	Melfort, high OM	alfalfa-bromegrass hay	WAS fast-wet	45.7	52.4–62.4	115–137
Campbell et al., 1993b	334	25	Swift Current	grain lentil	WAS fast-wet	15.1	31.6–34.2	209–227
Campbell et al., 1993b	355	27	Scott	alfalfa-hay	WAS fast-wet	26.8–32.8	48.6–54.9	149–205
Clay Loam								

Table 1.6 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR (%)
Malhi et al., 2009	355	12	Wheat, barley, canola, legume rotations	Legume/Brassica (pea, lentil, mustard GM)	MWD (mm)	10.67	19.31	115–120
Silt								
Blanco-Canqui et al., 2013	1,375	39	Soybean	Grass (winter/spring triticale)	MWD (mm)	0.50	0.85	170
Blanco-Canqui et al., 2013	1,375	39	Soybean	Legume (spring pea/lentil)	MWD (mm)	0.5	0.75	150
Blanco-Canqui et al., 2013	1,375	39	Soybean	Legume (winter lentil)	MWD (mm)	0.50	0.50	100

1.3.4 Water Infiltration

Infiltration controls how quickly water enters the soil profile, influencing runoff and plant-available water (Cornelis et al., 2019). Cover crops can improve infiltration by reducing surface crusting, creating bio pores through root channels, and adding organic matter that stabilizes soil structure (Basche & DeLonge, 2019). However, responses varied with soil texture, management, and climate (Table 1.7).

In clay loam soils, hairy vetch increased steady-state infiltration relative to fallow after just three years (RR = 154–176%, 54–76% gain; McVay et al., 1989), and long-term no-till with a cover crop mix produced infiltration about 2.8 times faster than no-cover plots in California (RR ≈ 280%, 180% gain; Mitchell et al., 2017). In silt loam soils, sunn hemp increased infiltration over 15 years in Kansas (RR = 282%, 182% gain), though late-maturing soybean showed no significant effect despite a similar numerical increase (Blanco-Canqui et al., 2011). Cereal rye increased infiltration rates during the off-season in Maryland (RR = 285–562%, 185–462% gain; Steele et al., 2012), and winter rye improved rates in South Dakota (RR = 127–180%, 27–80% gain; Chalise et al., 2019). In humid subtropical cotton systems, balansa clover (Trifolium *michelianum*) and rye increased infiltration relative to bare no-cover plots (RR = 488%, 388% gain and RR = 280%, 180% gain, respectively; Locke et al., 2013). In contrast, no improvement was observed in silty clay loam soils after 12 years in Nebraska (Blanco-Canqui & Jasa, 2019), and winter rye did not affect infiltration in an irrigated corn system when surface residues were retained (Sindelar et al., 2019). At the pore scale, one season of cover cropping increased macropore numbers by about 150% and produced a more complex pore structure,

suggesting cover crops begin reorganizing soil architecture within a single growing season (Cercioglu et al., 2018).

Overall, cover crop benefits to infiltration are greatest under long-term no-till management with adequate biomass and retained surface residues, while short-term and irrigated systems tend to show weaker or inconsistent responses.

Table 1.7. Effects of CC on water infiltration in soil across diverse climates, soils, and management systems
Abbreviations: CC = cover crop; C–S = corn–soybean; WW = winter wheat; NT = no-tillage; PAW = plant-available water; SCCC = single-species cover crop. Steele et al., (2012) results split by Coastal Plain vs. Piedmont environments.

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR %
Clay Loam								
McVay et al., 1989	1,100	3	NT, grain sorghum (Coastal Plain, GA)	Hairy vetch	Steady-state infiltration rate (mm h^{-1})	37.8 mm h^{-1} [1.59 min/mm]	58.4 mm h^{-1} [1.03 min/mm]	154
McVay et al., 1989	1,100	3	NT, corn (Limestone Valley, GA)	Hairy vetch	Steady-state infiltration rate (mm h^{-1})	22.0 mm h^{-1} [2.73 min/mm]	38.8 mm h^{-1} [1.55 min/mm]	176
Mitchell et al., 2017	344 (15-yr total)	15	NT, tomato–cotton (arid irrigated, CA)	CC mix (triticale, rye, vetch)	Single ring	1.60 min	0.57 min	164
Silt Loam								

Table 1.7 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR %
Blanco-Canqui et al., 2011	874	15	NT, wheat sorghum rotation	Sunn hemp	Steady-state infiltration rate (mm h^{-1})	1.7 cm h^{-1} [35.29 min/cm]	4.8 cm h^{-1} [12.50 min/cm]	182
Blanco-Canqui et al., 2011	874	15	NT, wheat sorghum rotation	Late-maturing soybean	Steady-state infiltration rate (mm h^{-1})	1.7 cm h^{-1} [35.29 min/cm]	3.5 cm h^{-1} [17.14 min/cm]	106
Chalise et al., 2019	~650	3	NT, corn soybean	Winter rye + hairy vetch	Steady-state infiltration rate (mm h^{-1})	61.7 mm h^{-1} [0.97 min/mm]	111 mm h^{-1} [0.54 min/mm]	180
Chalise et al., 2019	~650	3	NT, corn soybean	Winter rye + hairy vetch	Steady-state infiltration rate (mm h^{-1})	69.6 mm h^{-1} [0.86 min/mm]	88.5 mm h^{-1} [0.68 min/mm]	127

Table 1.7 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR %
Steele et al., 2012	1,033	13	NT, continuous maize	Cereal rye	Water infiltration rate (mm s^{-1})	1.41 mm s^{-1} [0.01 min/mm]	4.02 mm s^{-1} [0.00 min/mm]	185
Steele et al., 2012	1,033	13	NT, continuous maize	Cereal rye	Water infiltration rate (mm s^{-1})	0.317 mm s^{-1} [0.05 min/mm]	1.78 mm s^{-1} [0.01 min/mm]	462
Silty Clay Loam								
Blanco-Canqui & Jasa 2019	693	12	NT, corn soybean winter wheat	Grass CC (cereal rye, grain sorghum)	Cumulative infiltration	~47 cm [~3.83 min/cm]	~48 cm [~3.75 min/cm]	102

Table 1.7 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR %
Blanco-Canqui & Jasa 2019	693	12	NT, corn soybean winter wheat	Legume CC (winter pea, soybean)	Cumulative infiltration	~47 cm [~3.83 min/cm]	~50 cm [~3.60 min/cm]	106
Humid Subtropical (Silt Loam)								
Locke et al., 2013	Humid subtropical	6	NT + MT, cotton	Rye CC (plant row, 2006)	Steady-state infiltration rate (mm h^{-1})	17.6 mm h^{-1} [3.41 min/mm]	49.3 mm h^{-1} [1.22 min/mm]	180
Locke et al., 2013	Humid subtropical	6	NT + MT, cotton	Balansa clover (plant row, 2006)	Steady-state infiltration rate (mm h^{-1})	17.6 mm h^{-1} [3.41 min/mm]	85.9 mm h^{-1} [0.70 min/mm]	388
Loam								

Table 1.7 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR %
Kaspar et al., 2001	850	3	NT, corn soybean	Cereal rye (untracked interrow, 1998 only)	Steady-state infiltration rate (mm h^{-1})	10.87 mm h^{-1} [5.52 min/mm]	13.00 mm h^{-1} [4.62 min/mm]	119
Mexico Silt Loam								
Cercioglu et al., 2018	~1,130	1	NT, corn 0–20 cm depth	CC mix (cereal rye, hairy vetch, winter pea)	Number of macropores (per 2500 mm^2)	14	21	150
Cercioglu et al., 2018	~1,130	1	NT, corn 0–20 cm depth	cereal rye, hairy vetch, Austrian winter pea)	Pore circularity (0–1) [higher = more circular pores]	0.513	0.552	107

Table 1.7 continued

Reference	Precip. (mm)	Dur. (yr)	System	CC Type	Metric	No-CC	CC	RR %
Cercioglu et al., 2018	~1,130	1	NT, corn 0–20 cm depth	CC mix (cereal rye, hairy vetch, Austrian winter pea)	Fractal dimension of macropores [higher = more space-filling pores]	1.706	1.877	110

1.3.5 Hydraulic conductivity and plant available water

Hydraulic conductivity (Kfs) and plant available water (PAW) are key soil properties that regulate water movement and storage within the soil profile. PAW represents the portion of soil water available to plants between field capacity and the permanent wilting point, while Kfs reflects the ease with which water moves through soil pores under saturated conditions. Together, these properties influence water availability, root development, and crop resilience to both drought and excess moisture (Cornelis et al., 2019). Cover crops (CC) can influence these properties by improving soil structure, increasing organic matter, and enhancing pore connectivity (Haruna et al., 2018).

Responses of PAW and Kfs to CC management across soil textures, climates, and management durations are summarized in Table 1.8. In humid and sub-humid environments (> ~800–1200 mm annual precipitation), CC generally improved soil hydraulic properties. For example, in Ontario clay loam soils, CC increased near-surface saturated hydraulic conductivity and shifted water movement from surface runoff to subsurface drainage (Drury et al., 2014). Similarly, cereal rye improved infiltration-related parameters, including sorptivity and Kfs, in Missouri silt loam soils (Haruna et al., 2018). In loamy sand soils of Georgia, legume CC such as sunn hemp and crimson clover increased soil carbon and improved PAW, particularly in surface layers (Hubbard et al., 2013)

However, CC effects were not consistent across all systems. In silty clay loam soils under moderate annual precipitation (~693 mm), no significant differences in Kfs or PAW were observed among CC treatments or compared to fallow (Irmak et al., 2018; Blanco-Canqui and Jasa 2019). Similarly, studies in silt loam soils reported no measurable changes in water retention

following short-term CC adoption (Rorick and Kladivko 2017). These findings indicate that CC may have limited effects on soil water properties in systems with already stable structures or insufficient biomass production.

In some systems, modest improvements in PAW were observed. For example, PAW increased 1-2% under CC compared to conventional corn–soybean systems, with the highest values observed under mixed legume–grass systems (Villamil et al., 2006). However, the magnitude of change was relatively small compared to improvements observed in soil structure or aggregation.

Overall, the influence of CC on Kfs and PAW is highly site-specific and depends on soil texture, precipitation, and management duration. Improvements are more likely in coarse-textured or degraded soils where CC can increase soil organic carbon and aggregation, whereas in finer-textured or well-structured soils, responses are often minimal. These results suggest that CC effects on soil water dynamics are conditional and closely linked to their ability to modify soil structure and organic matter over time.

Table 1.8. Effects of CC on hydraulic conductivity and plant-available water across diverse climates, soils, and management systems

Reference	Precip. (mm)	Dur (years)	Crop	CC	Impact
Silty Clay Loam					
Irmak et al., 2018	~693	12	C-S, WW	Grass (rye, sorghum); Legume (pea, soybean)	NS among treatments
Blanco-Canqui and Jasa 2019	693	12	C-S, WW	Grass (rye, sorghum); Legume (pea, soybean)	No impact on water retention or PAW
Clay Loam					
Drury et al., 2014	831	6	C-S with WW	Winter wheat	+near-surface Ks; CC+CDS shifted flow from runoff to drainage; CDS alone: NS on Ks
Silt Loam					

Table 1.8 continued

Reference	Precip. (mm)	Dur (years)	Crop	CC	Impact
Rorick and Kladivko 2017	—	4	C-S	Cereal rye	NS effect on water retention
Villamil et al., 2006	~1033	6	C-S	Hairy vetch, rye, vetch+rye mix	+1–2% PAW vs. C-S; highest under C-R/S-VR (26.4%)
Haruna et al., 2018	1095	2	CC	Cereal rye vs. no CC	2014: +Kfs 75–80% (till), 42–54% (NT); 2015: + sorptivity 82–90%, +qs 63%, +Kfs 48%
Loamy Sand					
Hubbard et al., 2013	~1192	4	Sunn hemp → crimson clover → sweet corn	Sunn hemp; crimson clover; fallow	CC (esp. sunn hemp): +soil C, +PAW, +soil structure; plant rows > interrow in PAW

1.4 Gaps in Literature and Study Justification

Despite extensive research on cover crops (CC), considerable uncertainty remains regarding their performance in semi-arid dryland cropping systems of the Northern Great Plains (NGP). Many studies conducted in humid and high-precipitation regions report improvements in soil organic carbon (SOC), soil aggregation, nitrogen cycling, and soil hydraulic properties following CC adoption. However, results from semi-arid environments are often inconsistent because limited precipitation can restrict CC biomass production and increase the risk of soil water depletion for subsequent crops. Several studies across Montana and the central Great Plains have reported reductions in subsequent wheat yield when CC are grown in water-limited systems, particularly in environments receiving less than approximately 350–400 mm of annual precipitation. In addition, short-term studies in dryland systems frequently report minimal or inconsistent changes in SOC, soil aggregation, nitrogen use efficiency, and plant-available water.

Although some research suggests that CC may enhance nitrogen mineralization, biological fixation, and microbial-driven nitrogen transformations, the combined effects of CC and nitrogen management on crop productivity and soil health remain poorly understood in water-limited environments. Furthermore, many previous studies have focused on individual soil properties or were short-term experiments, and relatively few have evaluated the integrated effects of CC on crop yield, nitrogen use efficiency, SOC, soil aggregation, and soil water dynamics in dryland wheat-based systems. Because soil, climate, and precipitation patterns vary substantially across the NGP, region-specific data are needed to better understand the feasibility and management of CC in locations such as Huntley, Montana, where mean annual precipitation falls near the lower bound of conditions under which CC have been studied.

This study addresses these gaps by evaluating the impact of CC on wheat yield and soil health over multiple years in a field experiment in Huntley, Montana. By integrating measurements of SOC, infiltration, aggregation, substrate-induced respiration (SIR), plant-available water (PAW), nitrogen use efficiency, and grain protein content, this research provides a comprehensive assessment of CC performance under semi-arid conditions. The results will help inform region-specific management practices and contribute to the development of more resilient and sustainable dryland farming systems.

1.4.1 Chapters of this study

Chapter 2 establishes the background and framework for the CC system examined in this study. It provides the context for the research objectives, followed by a historical perspective of the experimental field at Huntley, including past management practices and the original study design. The chapter examines how past management decisions and the evolution of the field shape the current research environment, and how plot layout, species mixture, and management interact with the unique soil and climate conditions of the region. By integrating historical context and site-specific conditions, this chapter provides the foundation for understanding how experimental design and environmental factors together influence outcomes. The chapter also situates the study within regional climate trends in temperature and precipitation that influence both crop growth and soil function.

Chapter 3 evaluates the influence of CC on wheat productivity. Using the multi-year dataset, it examines yield trends, nitrogen use efficiency (ANUE), and grain protein content under different treatments. The chapter considers how CC presence, species mixture, and

management interact with weather patterns to shape yield outcomes. It integrates effective precipitation patterns and nitrogen dynamics to assess both the direct and indirect effects on wheat productivity. By linking yield performance to environmental conditions, this chapter provides insight into the mechanisms through which CC can enhance or challenge wheat production in a semi-arid system.

Chapter 4 investigates the sustainability implications of CC management by examining key indicators of soil health within the study system. This chapter focuses on physical, chemical, and biological soil properties that influence long-term agricultural sustainability. Specifically, it evaluates treatment effects on five metrics: aggregate stability, infiltration rate, total soil carbon, PAW, and SIR. By integrating multi-year management effects across soil depths and treatments, the chapter explores relationships between CC functional diversity and soil processes. It highlights potential pathways through which CC contribute to improvements in soil structure, enhanced water retention, and increased biological activity. Together, these analyses provide insight into the capacity of CC systems to maintain or improve soil function in dryland agricultural environments.

Chapter 5 synthesizes the results from both the crop productivity and soil health analyses and provides a comprehensive discussion of the overall impacts of CC in the study system. It integrates findings on wheat yield, nitrogen dynamics, and soil health indicators to evaluate the broader implications of CC management in semi-arid dryland cropping systems. The chapter discusses how CC treatments influence both agronomic outcomes and soil sustainability, highlighting potential trade-offs between crop productivity and soil improvement. It also places the results within the broader context of regional dryland agriculture and previous research.

Finally, it presents the Overall conclusions of the study and identifies key management implications and future research needs for optimizing CC systems in environments such as Huntley, Montana.

CHAPTER TWO: MATERIALS AND METHODS

2.1 Important Context of the Study

Cover crops play a vital role in sustainable agriculture. They enhance surface residue, help reduce soil erosion (Lu et al., 2000), and contribute to soil health by influencing soil organic matter, aggregation, nutrient cycling, and microbial activity. However, the overall benefit depends heavily on management practices, such as species selection, seeding time, and termination time, as well as climate conditions (Tonitto et al., 2006; Sharma et al., 2018. In water-limited dryland systems, however, the extent to which management practices can overcome climatic constraints remains uncertain, and the relative influence of inter-annual precipitation variability versus management factors on agronomic outcomes is not well quantified in this region. In drylands where rainfall and soil moisture are limiting, the effects of CC functional groups and mixtures on soil water dynamics, biological activity, and overall productivity remain poorly understood (Zhang et al., 2023). The objective of this study was to evaluate the effects of CC on subsequent spring wheat yield and soil health in a water-limited dryland system, and to determine how interannual variation in precipitation influences these responses.

2.2 Historical Perspective of Study Field

Before the current experimental design was established in 2018, the field had already been used for a similar CC study from 2014 to 2017 under a different design. It is important to

mention this earlier work because it forms the foundation and historical context of the current research. The earlier trial followed a two-year rotation of mixed CC and spring barley. The CC treatments included 10 CC entries: 6 single-species crops and 4 functional-group mixtures, plus a chemical-fallow control (Table 2.1). The design was a randomized complete block layout with four replicates, and the plots were 4.75 m × 18.29 m. All planting was done under no-till conditions using a SeedMaster air drill. Barley was planted perpendicular to the previous year's CC in a strip–strip layout. Nitrogen fertilizer was applied in bands near the seed rows at four rates (0, 22–28, 45–56, and 67–78 kg N ha^{-1}), with rates adjusted each year based on yield goals. Residual soil N at planting was estimated rather than measured directly, and the range of N rates was used to evaluate yield response by regression, with yield expectations varying by season. Although this earlier study primarily focused on the effect of CC on barley yield response, it laid the foundation for the current research by establishing site history, soil conditions, and initial management practices. This prior design also helps explain the evolution of the present study: the fallow treatments remained on the same blocks across both studies, representing a continuous grain–fallow system, and the pea treatment was likewise maintained in the same plots.

Table 2.1. Cover Crop Treatments Used in 2014–2017 at SARC, Organized by Functional Group(species) and Mixture Type.

	Functional Groups	**Species**
Sole Crops	Grasses	Barley (Hordeum vulgare L.) – cool season Forage Sorghum (Sorghum bicolor L.) – warm season
	Legumes	Yellow Dry Pea (Pisum sativum L.) – cool season Early Maturity Soybean (Glycine max L., Group 0.8) – warm season
	Taproots	Safflower (Carthamus tinctorius L.) – warm season Purple Top Turnip (Brassica rapa L.) – cool season
Mixes	GL	Grass +Legume
	GT	Grass + Taproot
	LT	Legume + Taproot
	GLT (All)	Grass + Legume + Taproot
Control	Fallow	

2.3 Current Experimental Design of the Study

2.3.1 Site Description

The study was conducted at the Montana State University, Southern Agricultural Research Center (SARC) near Huntley, Montana (45.89° N, 108.24° W; elevation ~920 m) under dryland, no-till conditions. The experiment was originally established in 2018, with preliminary findings and supporting material reported by Khan and McVay (2019). The present analysis focuses on the years 2020–2024. The region has a semi-arid climate characterized by cold winters, hot summers, and large interannual variability in precipitation. During the study period, annual precipitation ranged from 280 to 557 mm (Huntley SARC weather station, 2020–2024).

Soils at the site are mapped as Fort Collins loam and Thurlow clay loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalfs and fine, smectitic, mesic Torrertic Haplustalfs, respectively). The surface soil (0–15 cm) averages approximately 2% organic matter, pH ~8.0, and a bulk density of ~1.4 g cm^{-3} (USDA-NRCS Web Soil Survey; site-level measurements, this study).

2.3.2 Experimental design and layout

The experiment follows a randomized complete block design (RCBD) with four replicates arranged in a strip–strip configuration. The study was established as a fully phased rotation consisting of two adjacent fields in which CC and spring wheat alternated annually. In

each year, one field was planted with CC treatments while the other was planted with spring wheat, and the fields switched roles the following year (Fig. 2.1). Soil sampling was conducted in the East field in June 2024.

Each CC treatment was planted as a strip measuring 4.6 m × 18.3 m. Treatments were arranged in four replications (blocks) and randomized within each replication (Fig. 2.1). During the wheat phase, four nitrogen (N) fertilizer rates were applied — 0, 56, 112, and 168 kg N ha^{-1} as strips running perpendicular to the CC strips. This created a strip–strip crossed design in which every CC treatment intersected each N rate within each replication (Fig. 2.1). Each resulting CC × N intersection was approximately 4.5 m × 4.5 m.

A total of eleven CC treatments were established (Table 2.2). Six of these treatments represented four functional groups (legumes, grasses, brassicas, and taproots) along with a fallow control and a single-species spring pea treatment. The remaining five treatments consisted of a full mixture of all four functional groups and four three-group "minus" mixtures (e.g., legumes + grasses + brassicas, omitting taproots). The species composition of each treatment is presented in Table 2.2. Although all 11 CC treatments were grown during the study, analysis presented in this thesis focuses on a subset of seven treatments (fallow, spring pea, the four single-functional-group mixes, and the full mixture), excluding the four "minus" treatments to strengthen interpretation.

2.3.3 Field operations

During the cover crop phase, fields were treated with glyphosate (RT3, Monsanto) at 1,260 g a.e. ha^{-1} prior to planting to control emerged weeds. Cover crop strips were planted

either in the last week of April or the first week of May, using a no-till air drill (SeedMaster, Saskatchewan, Canada) at the seeding rates listed in Supplementary Table S2.8, with species seeding rates adjusted proportionally to the number of species in each mixture. Cover crops were terminated in early August by rolling followed by a glyphosate application (RT3, Monsanto) at 1,260 g a.e. ha^{-1}, leaving residue on the soil surface.

Spring wheat (sp. Vida) was planted in early May, perpendicular to the cover crop strips using the SeedMaster no-till drill at the MSU-recommended seeding rate (~67 kg ha^{-1}). Four N fertilizer rates (0, 56, 112, and 168 kg N ha^{-1}) were applied as urea, banded approximately 2 cm to the side of and below the seed row; soil nitrate was not measured; we assumed approximately 50 lb NO_3-N ac^{-1} in the profile and applied a range of N rates, allowing optimum N rates to be identified through regression analysis. Cover crop biomass was sampled before termination by harvesting aboveground from a 1-m strip within each plot. Roots were extracted from the soil profile, separated from soil, washed, and combined with the corresponding above-ground material. All biomass samples were dried at 60 °C to constant weight and weighed to determine total biomass.

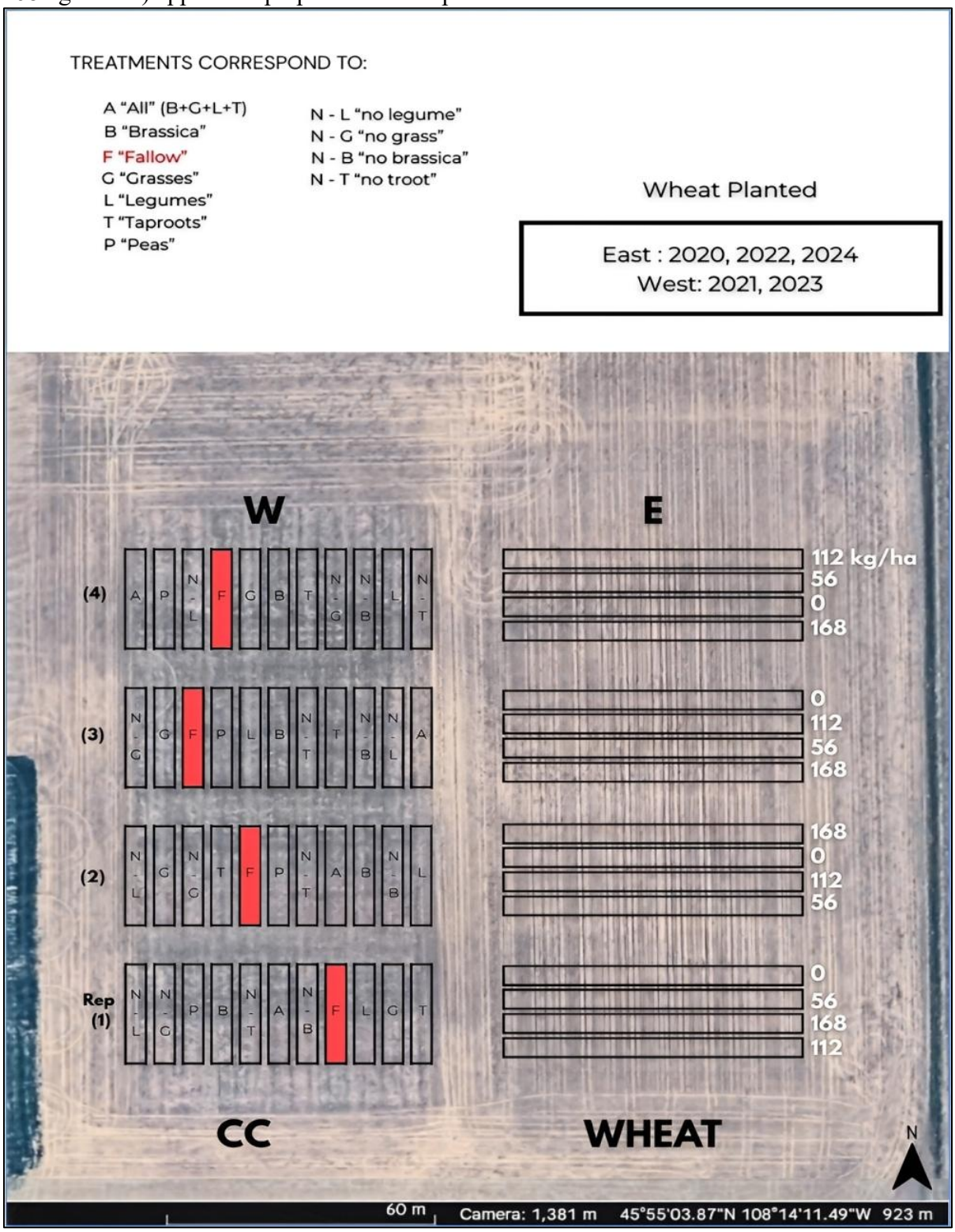
Table 2.2. Cover-crop functional groups and species composition, including the fallow control,

single-species pea, and mixed species (all 11 CC).

Treatment	**Functional Groups**	**Species**
1	Fallow (control)	
2	Legume mix	chickpea, cowpea, faba Bean, spring pea.
3	Taproot mix	buckwheat, flax, sunflower, safflower
4	Grass mix	corn, millet, oat, triticale
5	Brassica mix	canola, mustard, radish, turnip
6	all	A mixture of all functional groups (16 spp.)
7	Spring Pea	
8	No-Brassica	(legume + taproot + grass = 12 spp.)
9	No-legume	(taproot + grass + Brassica = 12 spp.)
10	No-grass	(legume + taproot + Brassica = 12 spp.)
11	No-taproot	(legume + grass + Brassica = 12 spp.)

Figure 2.1. Layout of the phased CC × nitrogen strip–plot design. Seven primary CC were randomized within four replications, and each plot was intersected by four N rates (0, 56, 112, and

168 kg N ha^{-1}) applied as perpendicular strips.



2.4 Climate and Growing Conditions

Huntley lies within the semi-arid climate zone of south-central Montana, characterized by cold winters, warm summers, and limited annual precipitation. During the study period, annual precipitation ranged from 280 mm (2021) to 557 mm (2023), with a five-year mean of 418 mm (Table 2.3). The site is located at 45.89° N, 108.24° W, at approximately 920 m (3,020 ft) elevation.

The region experiences a relatively short growing season, typically 120 to 130 frost-free days, which constrains planting dates, crop selection, and management practices. Because crop production relies entirely on stored soil moisture and seasonal precipitation, water availability is one of the most critical factors affecting crop performance. These climatic conditions make the region well-suited for evaluating CC management in dryland wheat systems, where the balance between soil moisture use, precipitation variability, and crop productivity is a key consideration.

2.4.1 Weather data

Weather data for 2020–2024 were obtained from the Daymet Single-Pixel Point Data Extraction Tool (https://daymet.ornl.gov/single-pixel/) for the Huntley site coordinates. Weather data were summarized by crop year, defined as August of the previous year through April of the harvest year, representing soil-water recharge and early-season moisture availability for spring wheat (e.g., crop year 2020 = August 2019 to April 2020). In addition, growing-season conditions (April–July) were summarized separately to characterize moisture availability during active wheat growth.

Potential evapotranspiration (PET) was estimated using the Thornthwaite method, a temperature-based approach widely applied in water-balance studies. Actual evapotranspiration (AET) — the combined loss of water through soil evaporation and plant transpiration — was estimated using a simple monthly water-balance approach in which PET sets the upper limit on water loss (AET ≤ PET), with AET further limited by the water available from precipitation plus stored soil water. When stored soil water supplements incoming precipitation, AET in a given period may exceed precipitation for that period.

Effective precipitation (EP) was defined as a climatic water-balance index representing the precipitation remaining after evapotranspiration demand has been met, calculated as the difference between precipitation (P) and actual evapotranspiration (AET):

$$EP = P - AET$$

Effective precipitation was bounded at zero. Negative values of P − AET indicate that evapotranspiration demand drew on both precipitation and stored soil water, representing a soil-water deficit; these were set to 0 mm. In this dataset, the only negative value occurred in the 2021 growing season (EP = −23 mm; Table 2.4), the driest year of the study, reflecting an evapotranspiration demand that exceeded growing-season precipitation.

The Thornthwaite method is temperature-based and does not account for vapor pressure deficit, wind, or net radiation; it therefore tends to underestimate AET under semi-arid conditions, which means EP as calculated here may be overestimated relative to true moisture surplus. Despite this limitation, EP is used throughout this study as a relative index of seasonal water availability to distinguish wet and dry years rather than as an absolute estimate of plant-available water; rankings of years by EP are unlikely to change substantially under alternative ET estimation methods.

2.4.2 Crop-year moisture conditions

Across crop years, precipitation (August–July) ranged from 280 mm in 2021 to 545 mm in 2020 (Table 2.3), with EP ranging from 74 mm to 236 mm, indicating substantial interannual variability in stored soil moisture entering the wheat phase.

Table 2.3. Crop-year Precipitation (P), Actual Evapotranspiration (AET), and Effective Precipitation (EP) for spring wheat grown from 2020 to 2024 at the SARC Huntley site.

Year	**P (mm)**	**AET (mm)**	**EP (mm)**
2020	545	309	236

2021	280	206	74
2022	369	275	94
2023	557	281	175
2024	337	261	76

2.4.3 Growing-season water balance

Growing-season precipitation (April–July) ranged from 96 mm in 2021 to 269 mm in 2023 (Table 2.4). In 2021, AET exceeded precipitation by approximately 23 mm, indicating a soil-water deficit during the growing season; EP was therefore reported as 0 mm. In contrast, 2020 received the highest precipitation and the largest EP (57 mm), reflecting favorable moisture conditions for crop development.

Table 2.4. Growing season (April-July) precipitation (P), Actual evapotranspiration (AET), and

effective precipitation (EP) for each year from 2020 to 2024 at the SARC Huntley site.

Year	P (mm)	AET (mm)	EP (mm)
2020	249	192	57
2021	96	119	-23
2022	243	195	48
2023	269	215	53
2024	191	161	29

Table 2.5. Comparison of crop-year, growing-season, and non-growing-season precipitation for each year from 2020 to 2024 at the SARC Huntley site.

Year	Crop-Year P (mm)	Growing-Season P (mm)	Non-Growing-Season P (mm)
2020	545	249	296
2021	280	96	184
2022	369	243	126
2023	557	269	288
2024	337	191	146
Mean	418	210	208

2.5 Soil Sampling

Soil samples were collected from the East field during the summer of 2024 from the seven primary cover crop treatments to assess CC effects on soil properties. Soil cores were collected using a soil core sampler (AMS, Inc., American Falls, ID).

Each plot consisted of four nitrogen-rate strips applied perpendicular to the CC strips. Sampling was conducted within two of these four N strips: the 0 kg N ha^{-1} (control) and the 112 kg N ha^{-1} rate. Within each selected N strip, four soil cores were collected in a diagonal pattern, approximately 0.9–1.2 m inside the plot boundary to minimize edge effects. Each core was sectioned in the field into two depth increments, 0–5 cm and 5–10 cm , and the sections were kept separate. The four upper sections (0–5 cm) from the diagonal cores were combined and thoroughly mixed to form one composite sample for that depth; the same procedure was repeated with the four lower sections (5–10 cm) to form a second composite. This was done independently within each of the two N strips, yielding four composite samples per plot (two depths × two N rates).

With four replications per CC treatment, this produced 8 composite samples per treatment per depth (4 reps × 2 N rates), or 16 composite samples per treatment in total across both depths and both N rates. A portion of each composited sample was transferred into labeled jars and submitted for laboratory analysis.

The experiment included four replications per treatment, resulting in:

$$4\ samples\ per\ plot \times 4\ replications = 16\ samples\ per\ treatment$$

2.6 Wheat Yield Evaluation Methods

2.6.1 Wheat yield determination

Wheat grain was harvested at maturity each year using a Wintersteiger plot combine (Wintersteiger AG, Ried im Innkreis, Austria), with straw and non-grain residue returned to the field. Grain moisture and test weight were measured using a GAC 2100 grain analyzer (DICKEY-john Corp., Auburn, IL). Plot yield (kg ha^{-1}) was standardized to a 13% moisture basis using:

$$Yield\ (kg\ ha^{-1}) = \frac{plot\ weight \times (100 - \%\ sample\ moisture)}{plot\ area \times 87}$$

where 87 represents the dry-matter fraction at 13% moisture (100 − 13).

2.6.2 Grain Protein Analysis

Grain protein content (%) was measured using a Perten near-infrared spectroscopy (NIRS) analyzer (Model IM9500, Perten Instruments, Hägersten, Sweden). Protein was reported on a 12% moisture basis because this matches the moisture content of the Perten factory calibration dataset for hard red spring wheat; this is standard practice for the instrument and follows the manufacturer's recommended procedure. Note that yield and grain protein are therefore reported on different moisture bases (13% and 12%, respectively), per their respective industry conventions.

2.6.3 Agronomic nitrogen-use-efficiency (ANUE)

N-Based ANUE provides an estimate of the direct fertilizer contribution to grain N accumulation and is widely used for evaluating fertilizer-N responsiveness in cropping systems. In the present study, N-Based ANUE was selected instead of the traditional grain-yield–based ANUE because grain N provides a more precise indicator of fertilizer-N recovery, particularly under variable grain protein concentrations and CC legacy effects on soil N availability. Higher ANUE values indicate more efficient uptake of fertilizer N into harvested grain; low ANUE values suggest reduced N recovery due to environmental losses, limited crop uptake, or CC legacy effects on soil N supply.

Grain nitrogen for each plot was derived from grain yield and grain protein concentration using the conventional protein-to-nitrogen conversion factor of 6.25:

$$Grain\ N\ (kg\ N\ ha^{-1}) = Yield\ (kg\ N\ ha^{-1}) \times (\frac{protein\ \%}{100}) \times 0.16$$

where 0.16 is the reciprocal of 6.25. This conversion factor is commonly used to estimate grain nitrogen concentration from measured grain protein concentration. Grain N was subsequently used to calculate agronomic nitrogen use efficiency (ANUE) and related nitrogen response metrics.

Agronomic nitrogen-use efficiency was then calculated on a grain-N basis (N-Based ANUE):

$$ANUE\% = \frac{(Grain\ NF - Grain\ N0)}{Napplied \times 100}$$

where Grain NF is the grain N in the fertilized plot (kg N ha^{-1}), Grain N0 is the grain N in the unfertilized (0 N) plot, and N applied is the fertilizer N rate (56, 112, or 168 kg N ha^{-1}).

2.7. Soil Health Evaluation Methods

We selected six soil health metrics to evaluate cover crop impacts on soil physical, chemical, and biological properties. These included three physical properties (bulk density, plant-available water, and aggregate stability), one chemical property (total carbon), one biological property (substrate-induced respiration), and one hydraulic property (infiltration).

2.7.1 Bulk Density

Soil bulk density was measured to support plant-available water calculations and to verify that cover crop treatments did not alter soil physical structure. Undisturbed soil cores were collected at 0–5 cm and 5–10 cm depth using a 2-inch diameter stainless steel bulk density ring sampler with a ring volume of 90.59 cm^3 (AMS, Inc., American Falls, ID; https://www.ams-samplers.com/2-x-6-soil-core-sampler-complete/). Cores were oven-dried at 105°C for 24 hours, and bulk density (g cm^{-3}) was calculated as dry soil mass divided by ring volume. Bulk density did not differ significantly across cover crop treatments at both depths ($p > 0.05$; Table 2.6).

Table 2.6. Soil bulk density (g cm^{-3}; mean ± SE) at 0–5 cm and 5–10 cm depths by cover crop treatment. No significant differences were detected among treatments at either depth ($p > 0.05$).

	0-2 inches depth		**2-4 inches depth**	
plant	**mean_BD**	**se_BD**	**mean_BD**	**se_BD**
All	1.2	0.10	1.1	0.14
Brassica Mix	1.3	0.11	1.4	0.08
Fallow	1.3	0.08	1.2	0.13
Grass Mix	1.3	0.16	1.2	0.12
Legume Mix	1.1	0.10	1.4	0.10
Pea	1.3	0.10	1.3	0.11
Root Mix	1.2	0.07	1.5	0.13
AVG	**1.2**		**1.3**	

2.7.2 Aggregate stability

Aggregate stability reflects the ability of soil aggregates to resist breakdown from external stresses such as raindrop impact, swelling-shrinking cycles, and tillage (Rohošková and Valla, 2004). It is an important indicator of soil structure, influencing water infiltration, aeration, erosion susceptibility, and biological activity (Le Bissonnais and Arrouays, 1997).

Wet aggregate stability was measured using a wet-sieving apparatus (Model M-0813E, Royal Eijkelkamp, Giesbeek, Netherlands) following the standard wet-sieving procedure described by Klute (1986). A 4.0-g subsample of air-dried 1–2 mm aggregates was placed on a 0.25-mm sieve, pre-moistened, and submerged in distilled water. Sieves were oscillated vertically for 3 minutes at approximately 34 cycles min^{-1} with a stroke length of 1.3 cm, allowing unstable aggregates to break apart and pass through the sieve into the pan below. The fraction remaining on the sieve was then dispersed using a sodium hexametaphosphate solution (2 g L^{-1}) to recover the sand and coarse-mineral fraction. Both fractions were oven-dried at 110

°C and weighed. Wet-aggregate stability (WAS) was calculated as the proportion of the original sample mass that remained as stable aggregates, corrected for sand and coarse debris:

$$WAS\ (\%) = \frac{Dry\ soil\ after\ wet\ sieving\ (g) - Sand\ fraction\ (g)}{Total\ dry\ soil\ before\ wet\ sieving\ (g) - Sand\ fraction\ (g)} \times 100$$

where the numerator represents the mass of stable aggregates and the denominator represents the mass of aggregable material in the original sample (Royal Eijkelkamp, 2022).

2.7.3 Infiltration rate

Soil infiltration rate reflects the capacity of soil to absorb and transmit water and is an important indicator of soil structure and management effects on soil health (Basche and DeLonge, 2019). Conservation practices such as no-till and cover cropping have been associated with increases in infiltration capacity over time, particularly through improvements in macroporosity and aggregate stability (Basche and DeLonge, 2019).

Field-saturated hydraulic conductivity (Kfs), an integrated measure of near-surface infiltration capacity, was measured using a SATURO dual-head infiltrometer (METER Group, Inc., Pullman, WA, USA) following the dual-head pressure method of Reynolds and Elrick (1990). A 15.2-cm diameter ring was inserted 5 cm into the soil; the instrument then automated water delivery, pressure regulation, and steady-state flow measurement at two sequential pressure heads. Kfs was calculated by the SATURO firmware from the Reynolds and Elrick (1990) two-ponding-head equation, which accounts for ring geometry and a soil-texture-dependent α-factor relating matric flux potential to Kfs. Output values were converted to mm h^{-1} for reporting.

Infiltration measurements are inherently variable in the field. The manufacturer reports coefficients of variation (CV) for Kfs of approximately 45–170% depending on soil texture class, with finer-textured soils exhibiting greater variability than coarse-textured soils (METER Group, 2021). This high variability in Kfs measurements is well documented in the field infiltration literature and should be considered when interpreting treatment differences.

2.7.4 Soil total carbon

Cover crops contribute residue from both aboveground and root biomass, which, upon decomposition, can enrich soil organic matter (SOM; Zhang et al., 2023). On a mass basis, SOM is commonly estimated as approximately twice soil organic carbon (i.e., SOC ≈ 0.5 × SOM), although this ratio varies with soil texture and SOM composition.

Soil total carbon (TC) was determined by Ward Laboratories, Inc. (Kearney, NE, USA) using high-temperature dry combustion (Nelson and Sommers, 1982). Total carbon measured by combustion includes both soil organic carbon (SOC) and any inorganic carbon (IC) present as carbonate minerals. At the SARC Huntley site, surface soils (0–10 cm) are characterized by limited carbonate accumulation in the upper profile despite a slightly alkaline pH (~8.0), consistent with site characterization reported by McVay and Khan (2022) for similar soil near the present study. The contribution of IC to combustion-derived TC at this depth is therefore expected to be small, and TC values are interpreted as approximately equivalent to SOC for the purposes of comparing CC treatment effects in this study. Within-treatment comparisons are unaffected by any residual IC contribution because all treatments share the same IC background at the site.

2.7.5 Plant-available water

Plant-available water (PAW) represents the volume of water held in soil between field capacity and permanent wilting point and is a key determinant of crop water supply in dryland systems (Wang et al., 2009). Cover crop adoption can increase SOM and modify pore-size distribution, thereby improving PAW (Abdallah et al., 2021; Basche and DeLonge, 2019).

Plant-available water was determined using the pressure-plate method (Klute, 1986). Soil samples collected at two depths (0–5 cm and 5–10 cm) and two N levels (0 and 112 kg N ha^{-1}) were packed into 1-cm tall rings placed on pre-wetted ceramic pressure plates and saturated by the addition of deionized water. Samples were then equilibrated at 10 kPa (0.1 bar; field capacity) and 1500 kPa (15 bar; permanent wilting point) using a pressure-plate apparatus (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Once equilibrium was reached, samples were removed, weighed, oven-dried at 105 °C, and reweighed to determine gravimetric water content (Klute, 1986).

Gravimetric water content (θg, g g^{-1}) was calculated as:

Volumetric water content (θv, cm^3 cm^{-3}) was calculated by multiplying gravimetric water content by the mean bulk density for each depth and dividing by the density of water

$$\theta_v\ (cm^3\ cm^{-3}) = \frac{\theta_g \times \rho_b}{\rho_w}$$

Plant-available water (PAW, cm^3 cm^{-3}) was then calculated as the difference between θv at field capacity (0.1 bar) and θv at permanent wilting point (15 bar):

$$PAW\ (cm^3\ cm^{-3}) = \theta_(v(0.1\ bar)) - \theta_(v(15\ bar))$$

2.7.6 Substrate-induced respiration

Substrate-induced respiration (SIR) estimates the active microbial fraction of soil by measuring the respiratory response of microorganisms to a readily available carbon source (Blagodatskaya and Kuzyakov, 2013).

Air-dried soil samples were sieved to <2 mm. One gram of soil was placed into 100 mL crimp-sealed glass bottles, and 1 mL of yeast solution (1.2 g yeast per 100 mL distilled water) was added as a labile carbon substrate. Bottles were sealed and incubated at room temperature (~22 °C). Headspace gas (5 mL) was sampled by syringe at 5 and 24 hours post-incubation and injected into a LI-COR 850 CO_2 analyzer (LI-COR Biosciences, Lincoln, NE, USA) using nitrogen as a carrier gas. CO_2 concentrations in the injected gas were determined from peak height using a four-point standard curve and reported as CO_2 mixing ratio (µmol mol^{-1}, equivalent to parts per million by volume, ppmv). Respiration rates were expressed as µg CO_2-C g^{-1} soil h^{-1} using:

$$SIR\ (\mu g\ CO_2\text{-}C\ g^{-1}\ h^{-1}) = \frac{CCO_2\ (\mu mol\ mol^{-1}) \times V\ (L) \times 12}{24.45 \times W\ (g) \times t\ (h)}$$

where:

CCO2 = measured headspace CO_2 mixing ratio (µmol mol^{-1}, equivalent to ppmv), Vh = bottle headspace volume = 0.098 L (calculated as 100 mL bottle volume minus ~1 mL yeast solution and ~1 mL volume displaced by 1 g of soil, assuming soil bulk density ≈ 1.3 g cm^{-3}), 12 = atomic mass of carbon (g mol^{-1}), 24.45 = molar volume of an ideal gas at 25 °C and 1 atm (L mol^{-1}), W = mass of oven-dry equivalent soil (1 g), t = incubation time (5 or 24 h)

The factor (12 / 24.45) converts µmol of CO_2 to µg of carbon, yielding SIR in units of µg CO_2-C per gram of soil per hour.

2.8 Statistical analysis

All statistical analyses were conducted in R version 4.4.2 (R Project for Statistical Computing, https://www.r-project.org). Wheat yield, grain protein concentration, agronomic nitrogen-use efficiency (ANUE), and soil health indicators were evaluated using a combination of analysis of variance (ANOVA), linear mixed-effects models, and linear regression, depending on the structure of the data and the research objective.

Treatment effects for wheat yield, grain protein, and ANUE were analyzed within a randomized complete block design (RCBD) framework. The fixed effects of CC treatment (hereafter, CC) and nitrogen fertilizer rate (hereafter, N rate) were evaluated using ANOVA. To account for environmental variability across years and field positions, wheat yield was also analyzed using linear mixed-effects models (lme4 package in R), with CC, N rate, and their interaction as fixed effects and year, field (east/west), replicate, and the field-within-year interaction as random effects. This random-effect structure was chosen to capture both spatial (field) and temporal (year) variation within the strip–strip phased rotation, recognizing that the east and west fields experienced different precipitation in different years.

Relationships between environmental variables and crop performance were evaluated using linear regression. Specifically, the relationship between effective precipitation (EP) and wheat yield was examined to quantify how variation in water availability influenced yield responses across years. When statistically significant treatment effects were detected ($\alpha = 0.05$),

Fisher's protected least significant difference (LSD) test was used for mean separation; this method provides clear pairwise comparisons among treatments while maintaining appropriate error control following a significant overall ANOVA.

To quantify treatment magnitude relative to fallow, CC effects were expressed using response ratios (RR = CC ÷ Fallow), where RR > 1 indicates a positive treatment effect relative to fallow and RR < 1 indicates a negative effect. RR values were used throughout to standardize responses and facilitate interpretation across treatments, depths, and years.

For soil health indicators, treatment effects were evaluated using linear models including CC treatment, N rate, soil depth, and their interactions as fixed effects. This structure was used because soil measurements were collected across two depths and two N rates per plot, requiring evaluation of both main effects and interactions. Soil data were log-transformed where necessary to improve normality and meet model assumptions; model assumptions were verified using residual diagnostics (Q-Q plots, residuals vs. fitted plots). To assess the relative importance of predictors in soil models, partial η^2 (eta-squared) and ΔR^2 were calculated to quantify the contribution of individual factors to overall model variance. Statistical significance for all analyses was assessed at $\alpha = 0.05$.

CHAPTER THREE: DRIVERS OF WHEAT YIELD IN DRYLAND SYSTEMS: ROLES OF CC, NITROGEN, AND WEATHER

3.1 Abstract

Cover crop (CC) adoption in dryland wheat systems involves a fundamental tradeoff: potential agronomic benefits must be weighed against the risk of yield loss in environments where water is the primary limiting resource. This study evaluated the effects of six CC types and a fallow control, combined with four N fertilizer rates (0, 56, 112, and 168 kg N ha^{-1}), on spring wheat grain yield, grain protein concentration, and agronomic nitrogen use efficiency (ANUE) across five growing seasons at Huntley, Montana.

Inter-annual weather variability, measured as effective precipitation (EP), was the strongest factor evaluated in this study, substantially outweighing the influence of any management factor tested. Cover crop reduced wheat yield relative to fallow on average, though the magnitude varied by CC type and annual EP. Pea produced the smallest yield reduction and was the only CC type to significantly increase grain protein relative to fallow. The yield penalty was largest in low-EP years and smallest or absent in high-EP years, indicating that EP strongly mediated the agronomic impact of CC on the following wheat crop.

Grain protein increased, and ANUE declined with increasing N rate across both systems. In most years and N rate combinations, fallow systems achieved higher ANUE than CC, with differences most pronounced in high-EP years. These results suggest that CC type selection and

N management in semi-arid dryland systems should account for expected seasonal moisture conditions, which in this region can be partially anticipated from historical EP distributions and cool-season precipitation patterns.

Abbreviations: CC treatment = each CC, CC system = pooled CC category for fallow contrast.

3.2 Results

3.2.1 Drivers of wheat yield variability

Wheat yields varied strongly across years, fields, N rates, and CC systems (cover crop vs. fallow). Across all treatments, mean (±SD) yield was 1,770 ± 910 kg ha^{-1}, with annual means ranging from 988 ± 348 kg ha^{-1} in 2021 (the driest year) to 2,878 ± 800 kg ha^{-1} in 2020, a roughly 2.9-fold difference between the worst and best growing seasons (Table 3.2).

The mixed-effects model explained 93% of total yield variance (conditional R^2; Table 3.1). The dominant source of variation was the field × year interaction (environment), which accounted for 71% of total variance, confirming that site-specific and inter-annual conditions were the primary drivers of yield. Fixed effects (CC, N rate) collectively explained 8% of variance (marginal R^2), but their effect sizes were small relative to environmental variation.

N rate was the stronger of the two fixed effects ($\chi^2 = 49.37$, $p < 0.05$; partial $R^2 = 0.09\%$), with mean yields increasing from 1,443 ± 574 kg ha^{-1} at N0 to 2,137 ± 1,011 kg ha^{-1} at N112 and no additional response at N168 (2,087 ± 1,108 kg ha^{-1}; Table 3.2). Although N rate was statistically significant, the very small partial R^2 indicates that it explained only a negligible proportion of

total yield variance once environmental variation was accounted for. N rate influenced yield direction (more N produced higher yields up to N112) but explained almost none of the year-to-year and field-to-field variability that dominated the dataset.

The CC vs. fallow contrast was also statistically significant but likewise explained almost none of the wheat yield variance ($\chi^2 = 18.62$, $p < 0.05$; partial $R^2 = 0.02\%$). Numerically, fallow had the highest mean yield (2,257 kg ha^{-1}), exceeding every CC treatment, including All (1,772 kg ha^{-1}), when averaged across years and N rates (Table 3.2). The CC × N rate interaction was marginally non-significant ($\chi^2 = 7.63$, $p = 0.054$; partial $R^2 = 0.006\%$), and we interpret this term as inconclusive rather than meaningful. The environment × replicate × N rate interaction explained ~10% of the variance, the environment × replicate × CC treatment interaction explained ~5%, the environment × replicate interaction explained <1%, and the residual variance accounted for 6.5%.

Note on variance metrics. The fixed-effect rows and random-effect rows of Table 3.1 use different variance metrics because they answer different questions. Partial R^2 (fixed effects) reports the unique contribution of a single term after accounting for all other terms in the model. Variance share (random effects) reports each random component as a fraction of total model variance. Nakagawa marginal R^2 reflects the variance explained by all fixed effects together; conditional R^2 reflects fixed plus random effects combined. Because these metrics use different denominators, individual partial R^2 values are not expected to sum to marginal R^2.

Table 3.1. Mixed-effects model, (a) fixed-effect significance tests and partial R^2, (b) variance partitioning of random effects, and (c) overall model fit. Fixed-effect significance was assessed using Type III Wald chi-square tests. Fixed-effect rows report partial R^2 (unique contribution per term); random-effect rows report variance share (fraction of total model variance). Random-effect p-values are from likelihood-ratio tests (LRT) comparing the full model to a reduced model.

Section	**Term**	**Test statistic**	**p-value**	**Variance / R^2 metric**
Fixed effects	N rate	$\chi^2 = 49.37$	<0.05	Partial $R^2 = 0.09\%$
	System (CC vs. Fallow)	$\chi^2 = 18.62$	<0.05	Partial $R^2 = 0.02\%$
	System × N rate	$\chi^2 = 7.63$	0.054 [a]	Partial $R^2 = 0.006\%$
Random effects	Environment (Field × Year)	—	<0.05 [b]	Variance share = 71.4%
	Environment × Rep × N rate	—	0.5 [b]	Variance share = 9.8%
	Environment × Rep × Treatment	—	<0.05 [b]	Variance share = 5.1%
	Environment × Rep	—	<0.05 [b]	Variance share = 0.8%
Residual	Unexplained variance	—	—	Variance share = 6.5%
Model fit	Marginal R^2 (fixed effects total)	—	—	8%
	Conditional R^2 (fixed + random)	—	—	93%
	Random contribution (Conditional − Marginal)	—	—	85%

[a] Marginally non-significant at $\alpha = 0.05$; interpreted as inconclusive. [b] Likelihood-ratio test (LRT) p-value comparing full and reduced models.

Table 3.2. Mean wheat yield (kg ha^{-1}) by cover crop treatment, year, and nitrogen rate. Each block reports the mean averaged across

the other two factors (e.g., the cover crop block averages over years and N rates). Median and standard deviation are also shown to describe the distribution and spread.

Factor	Level	Mean yield (kg ha^{-1})	Median yield (kg ha^{-1})	SD (kg ha^{-1})
Cover crop	Fallow	2,257	1,695	1,129
	Pea	2,040	1,779	1,042
	Brassica Mix	2,027	1,748	852
	Legume Mix	1,949	1,869	988
	All	1,772	1,572	905
	Root Mix	1,741	1,509	811
	Grass Mix	1,719	1,351	929
Year	2020	2,878	3,054	800
	2021	988	976	348
	2022	1,270	1,223	292
	2023	2,736	2,750	727
	2024	1,593	1,597	380
N rate	0	1,443	1,316	574

Table 3.2 continued

Factor	Level	Mean yield (kg ha^{-1})	Median yield (kg ha^{-1})	SD (kg ha^{-1})
	56	1,905	1,597	853
	112	2,137	1,876	1,011
	168	2,087	1,783	1,108

Table 3.3. Variance partitioning (%) for wheat grain yield, grain protein concentration, and ANUE based on mixed-effects models. Values represent the proportion of total variability explained by environmental effects (field × year), nitrogen fertilizer rate, CC system (CC vs. fallow), and residual variance.

Response	Environment (Field×Year)	N rate	CC	Residual
Yield	71.4	1	0.3	6.5
Protein	74.8	3.1	0	5.7
ANUE	42.3	0.8	1.5	18.6

3.2.2 Wheat yield

3.2.2.1 Wheat yields following CC treatments. Wheat yield was significantly affected by year, CC system, N rate, replicate, and the CC × N rate interaction (Table 3.4). Year had the strongest effect on yield variability ($F = 171.6$, $p < 0.05$), with annual means (±SD) ranging from 988 ± 348 kg ha^{-1} in 2021 to 2,878 ± 800 kg ha^{-1} in 2020, consistent with inter-annual differences in EP discussed in Section 2.4.2. N rate ($F = 161.7$, $p < 0.05$) and CC system ($F = 10.1$, $p < 0.05$) were also statistically significant. Replicate was significant ($F = 6.3$, $p < 0.05$), indicating spatial variability across the field. The Year × CC ($F = 3.7$, $p < 0.05$), Year × N rate ($F = 40.9$, $p < 0.05$), and CC × N rate ($F = 1.5$, $p < 0.05$) interactions were all statistically significant, while the three-way Year × CC × N rate interaction ($F = 0.6$) was not.

Averaged across all five years and all N rates, yields following CC were lower than fallow for all treatments except pea (Table 3.2; Fig. 3.2). Response ratios for All (RR = 79%, 21% loss), grass mix (RR = 79%, 21% loss), root mix (RR = 80%, 20% loss), legume mix (RR = 83%, 17% loss), and brassica mix (RR = 84%, 16% loss) were all significantly below 100%. Only pea (RR = 90%, 10% loss) was not significantly different from fallow, with its 95% confidence interval overlapping 100% (Fig. 3.2). Year-by-year RR patterns for each CC treatment are shown in Fig. 3.1.

Figure 3.1. Response ratios (RR) of wheat yields following individual CC types (relative to following fallow) for 2020 to 2024. Points represent treatment means, with all four fertilizer rates averaged together, and error bars indicate 95% confidence intervals. The dashed red line denotes wheat yields following CC equal to wheat yields following fallow (RR = 1).

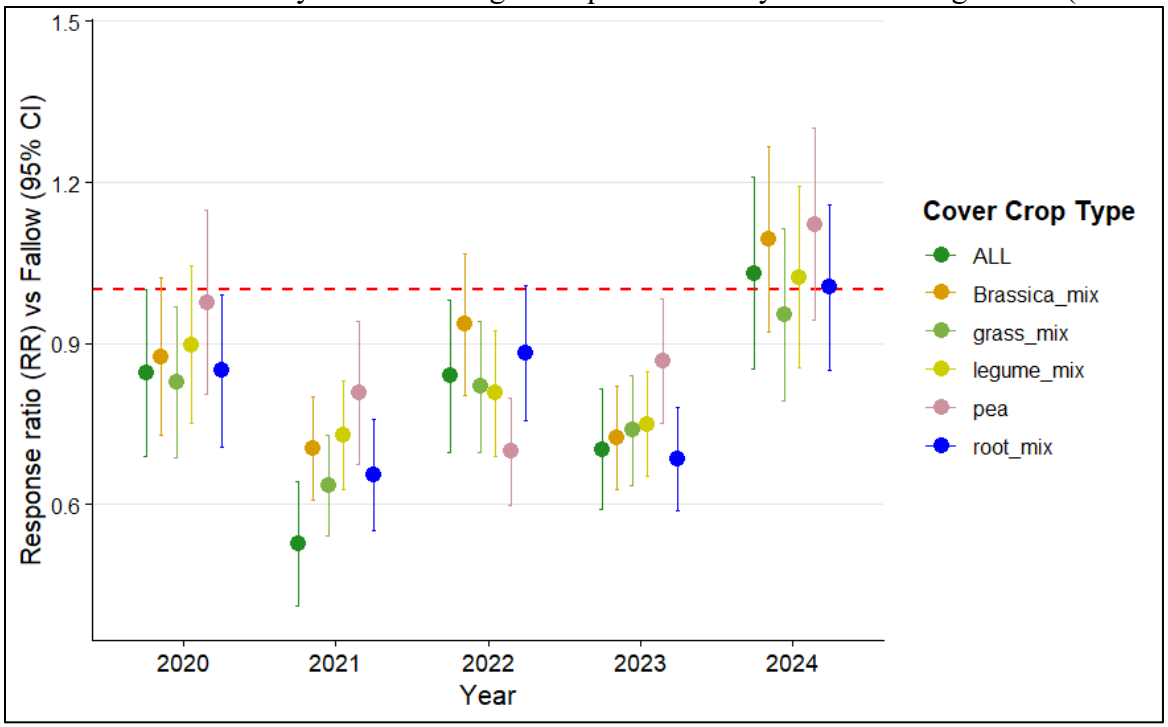


Figure. 3.2. Mean response ratio (RR = CC yield / fallow yield) for each CC treatment averaged across all five crop years (2020–2024) and all four N rates. Percentage labels indicate the mean yield difference relative to fallow. Points represent treatment means; error bars indicate 95% confidence intervals. The dashed red line denotes RR = 1. ns = not significantly different from fallow (Fisher LSD, α =

0.05); all other treatments are significant at $p < 0.05$. n = 4 replicates per treatment per year.

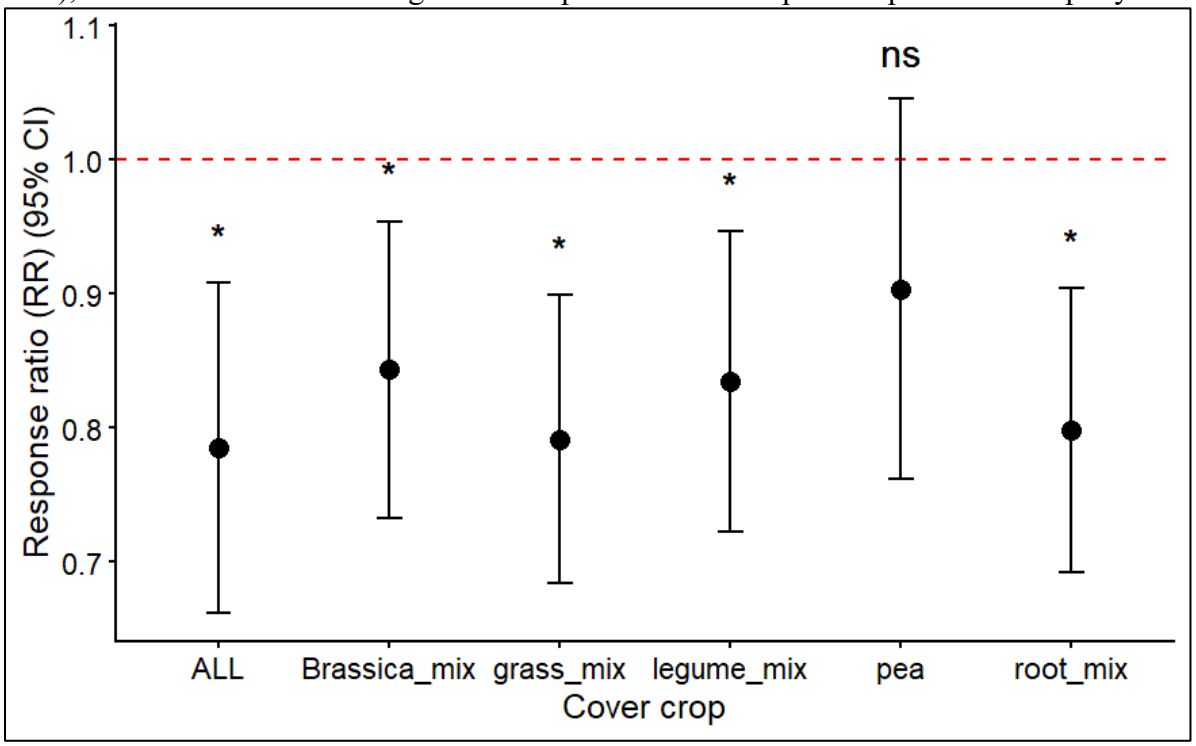


Table 3.4. ANOVA for yield with effects of year, N rate (nitrogen rates), CC(among CCs), and interactions ($\alpha = 0.05$).

Effect	**NumDF**	**F value**	**Pr(>F)**
Year	4	171.6	<0.05
CC	5	10.1	<0.05
N rate	3	161.7	<0.05
Rep	3	6.3	0.008
year:cc	20	3.7	<0.05
year:N rate	12	40.9	<0.05
cc:N rate	15	1.5	0.09
year:cc:N rate	60	0.6	0.99

3.2.2.2 Cover crop vs fallow. Averaged across all five years (2020–2024), wheat yield was approximately 17% lower under CC than under fallow, with mean yields ranging from 1,772 ± 905 kg ha^{-1} and 2,257 ± 1,129 kg ha^{-1}, respectively (Table 3.2).

The magnitude of the yield difference between CC and fallow varied by year and tracked with EP (Table 3.5; Fig. 3.3). Considering first the years grouped by EP: in the two lowest-EP years (2021: 74 mm; 2022: 94 mm), fallow yields were significantly greater than CC ($p < 0.05$). In 2021, the lowest-yielding year overall, CC averaged 28% below fallow (1,416 ± 300 kg ha^{-1} vs 1,013 ± 322 kg ha^{-1}). In 2022, CC averaged about 19% below fallow (1,273 ± 332 kg ha^{-1} vs. 1,581 ± 509 kg ha^{-1}). In the two highest EP years, the absolute yield gap was the largest. In 2023 (EP = 175 mm), CC averaged 26% below fallow (3,019 ± 430 kg ha^{-1} vs. 4,080 ± 359 kg ha^{-1}), consistent with greater soil water removal by CC in the preceding year compared to fallow. In 2020 (EP = 236 mm), CC averaged 12% below fallow (3,349 ± 388 vs 3,807 ± 551 kg ha^{-1}; $p < 0.05$). In 2024 (EP = 76 mm), CC yields were not significantly different from fallow ($p = 0.3$) and averaged 16% above fallow (Fig. 3.3), suggesting that low EP alone does not always produce a yield penalty and that year-specific factors, such as residue carryover, planting date, and cool-season precipitation also contribute to the magnitude of the CC effect in any given year.

Figure 3.3. Response ratio (RR) of wheat yields for all six CC relative (and all N fertilizer rates) to fallow from 2020 to 2024. Points represent annual means, and error bars indicate 95% confidence intervals. The dashed red line denotes parity with fallow (RR = 1).

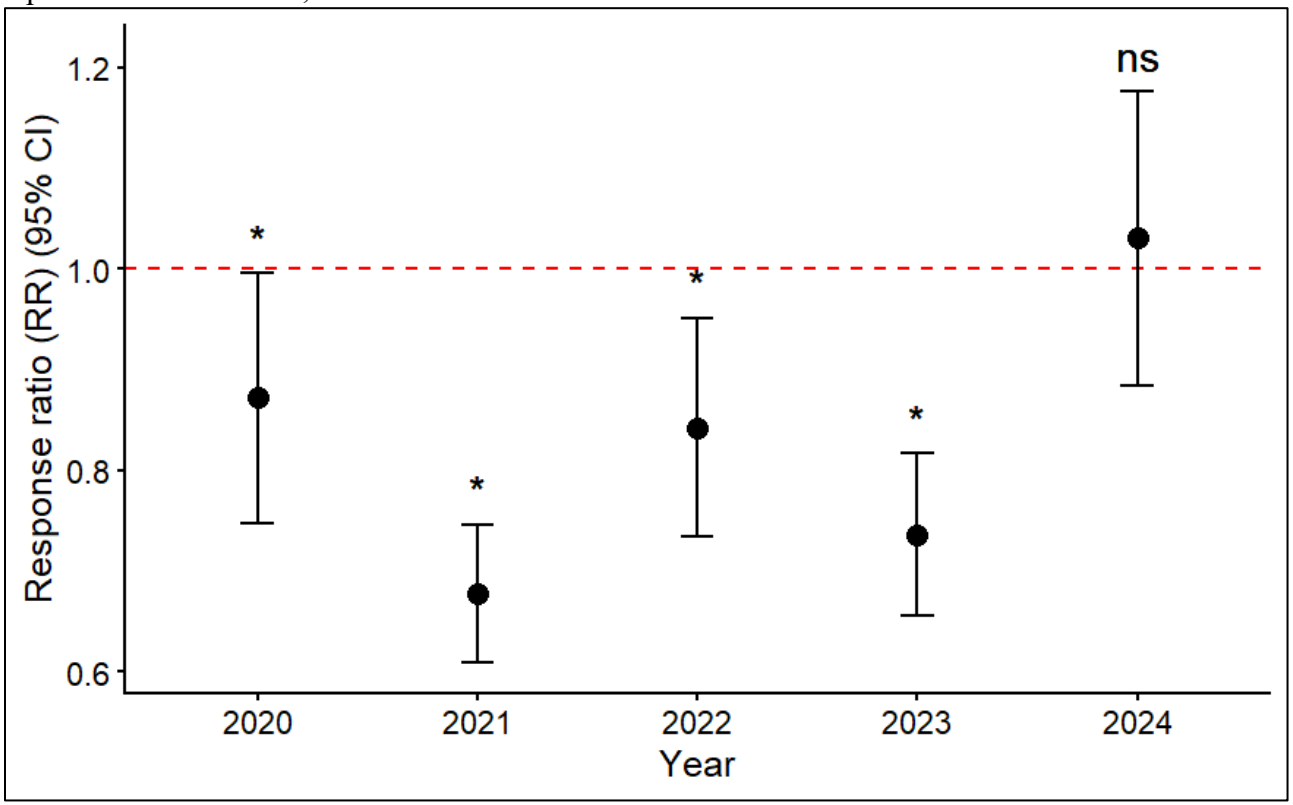


Table 3.5. Annual fallow and CC mean wheat yield and effective precipitation (EP) for crop years 2020–2024. Yields reported at 13% moisture (kg ha^{-1}); values are means ± SD averaged across all six CC treatments and four N rates. EP = growing-season effective precipitation (mm); see Section 2.4.1. Significance of CC vs fallow comparison by Fisher LSD ($\alpha = 0.05$): * $p < 0.05$; ns = not

significant. n = 4 replicates per year.

Year	EP (mm)	Fallow yield (kg ha^{-1}) Mean ± SD	CC yield (kg ha^{-1}) Mean ± SD
2020	236	3807 ± 551	3349 ± 388
2021	74	1416 ± 300	1013 ± 322
2022	94	1581 ± 509	1273 ± 332
2023	175	4080 ± 359	3019 ± 430
2024	76	1666 ± 243	1931 ± 304

3.2.3 Nitrogen effects on wheat yield

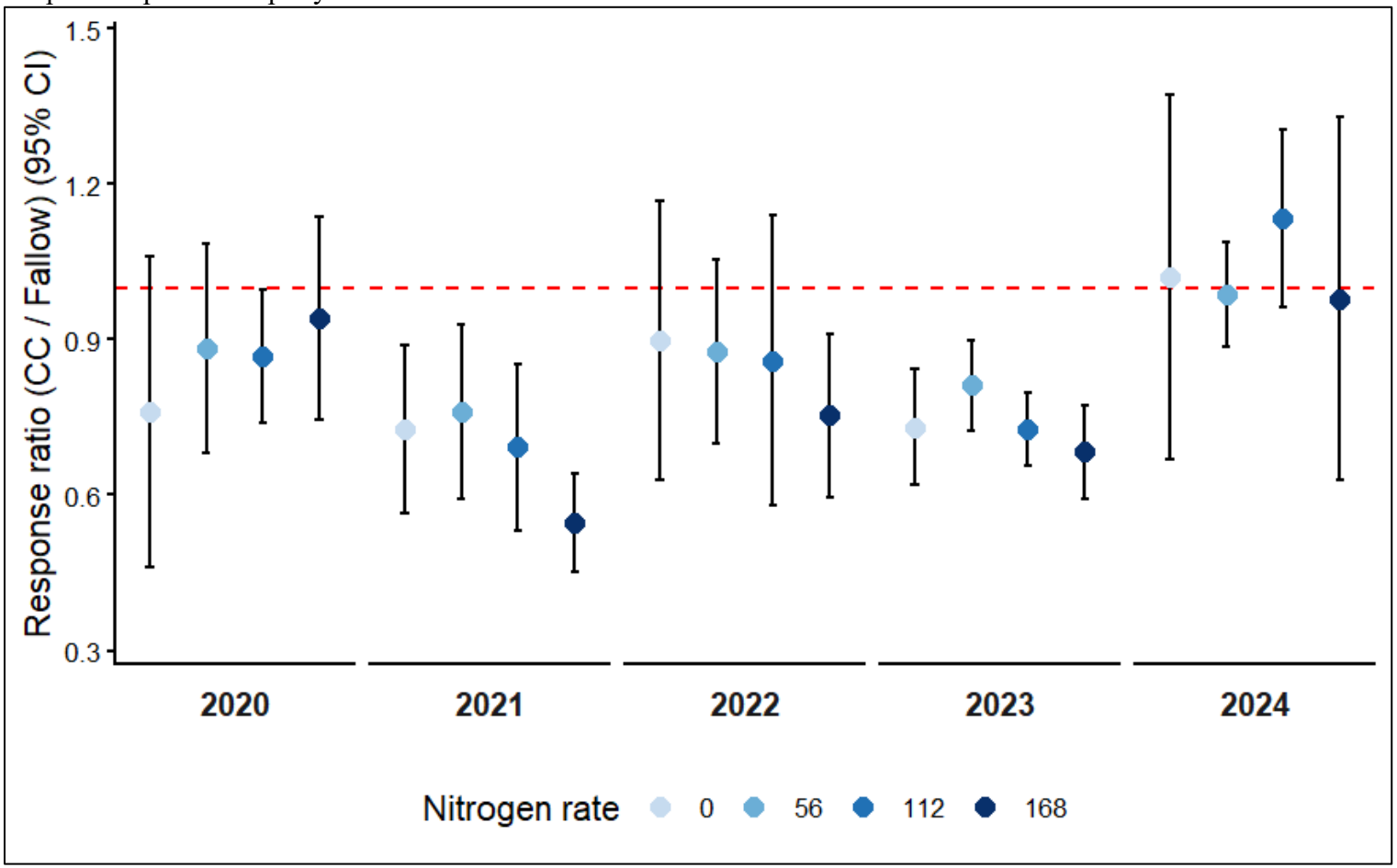
A fixed-effects ANOVA was used to examine the influence of N rate and its interactions with CC treatment and year on wheat yield (Table 3.4). Wheat yield responded positively to N fertilization across all years, with the magnitude of response varying by year (Table 3.2; Fig. 3.4). The largest yield gains occurred between 0 and 56 kg N ha^{-1}, with diminishing returns at higher rates, consistent with a curvilinear response. Yields generally peaked near 112 kg N ha^{-1} (marginal mean 2,137 kg ha^{-1}), with a slight decline at 168 kg N ha^{-1} (2,087 kg ha^{-1}), indicating reduced N use efficiency at the highest application rate (Table 3.2).

The Year × N rate interaction was statistically significant ($F = 40.9$, $p < 0.001$; Table 3.4), reflecting stronger yield responses to N in higher-EP years. In 2020 and 2023 (EP = 236 and 175 mm, respectively), yields increased with increasing N rate and showed a pronounced curvilinear response. In contrast, in lower-EP years (2021, 2022, and 2024; EP = 74, 94, and 76 mm, respectively), the response to added N was minimal, with yields largely constrained by water availability regardless of N rate, consistent with the dominant effect of year on yield variability in this dryland system ($F = 171.6$, $p < 0.001$; Table 3.4).

The CC × N rate interaction was not statistically significant ($F = 1.52$, $p = 0.093$; Table 3.4), indicating that the yield response to N fertilization did not differ systematically among CC treatments. Despite this, increasing N rate did not eliminate the yield gap between CC and fallow in any year (Fig. 3.4). Average across N rates, CC remained below parity with fallow in most years: RR = 76% (24% loss) in 2020, 73% (27% loss) in 2021, 90% (10% loss) in 2022, and 73% (27% loss) in 2023, but reached RR = 102% (2% gain) in 2024. At 112 kg N ha^{-1}, RR was 87% (13% loss), 86% (14% loss), 88% (12% loss), 73% (27% loss), and 113% (13% gain) for

2020–2024, respectively, but CC yields did not consistently reach parity with fallow at any N rate, indicating that N limitation alone did not account for the lower CC yields.

Figure. 3.4. Response ratio (RR = CC yield / fallow yield) by N rate (0, 56, 112, 168 kg N ha^{-1}) for crop years 2020–2024, averaged across all six CC treatments. Points represent treatment means; error bars indicate 95% confidence intervals. The dashed red line denotes RR = 1 (parity with fallow). Percentage labels indicate the mean yield difference relative to fallow at each N rate within each year. n = 4 replicates per N rate per year.



3.2.4 Weather effects on yield

Inter-annual wheat yield variation was strongly associated with EP in both fallow and CC systems (Table 3.5; Fig. 3.3). EP ranged from 74 mm in 2021 to 236 mm in 2020, and fallow yields tracked this variation closely, ranging from 1,416 ± 300 kg ha^{-1} in 2021 to 3807 ± 551 kg ha^{-1} in 2020, which is the second highest (Table 3.5). The CC yields followed a similar pattern, ranging from 1,013 ± 322 kg ha^{-1} in 2021 to 3349 ± 388 kg ha^{-1} in 2020, remaining below fallow in all years except 2024 (Table 3.5; Fig. 3.3).

In each year, wheat yield following fallow exceeded yield following CC under comparable EP conditions, consistent with the overall finding that CC systems produced lower wheat yields than fallow regardless of water availability (Fig. 3.3). The two lowest-EP years (2021: 74 mm; 2022: 94 mm) produced the lowest absolute yields, while the two highest-EP years (2020: 236 mm; 2023: 175 mm) produced the highest absolute yields and the largest absolute yield gaps between fallow and CC. In 2024, despite similarly low EP (76 mm) to 2021 and 2022, CC yields were not significantly different from fallow ($p = 0.3$; Fig. 3.3), indicating that EP alone does not determine the magnitude of the CC yield penalty.

3.2.5 Grain protein

Grain protein was significantly affected by year, CC type, and N rate (Table 3.6). N rate was the dominant driver ($F = 776.7$, $p < 0.05$), followed by year ($F = 119.8$, $p < 0.05$) and CC type ($F = 18.2$, $p < 0.05$). Among the interactions tested, only the year × N rate interaction was significant (Table 3.6), indicating that the magnitude of the protein response to N fertilization

varied across years, while the response to N did not differ among CC types. Year 2020 appeared to drive this interaction (Fig. 3.7), exhibiting a distinct protein response to N compared to other years, which showed similar response shapes to applied N despite differing in their baseline protein levels. This year-specific response likely reflects the strong influence of yield on grain protein concentration in years where yield response to N was large; dilution effects may have attenuated the protein increase per unit N applied, while in lower-yielding years the same N addition produced a steeper protein response.

Protein averaged 14 ± 2% across all treatments and years, ranging from 12 ± 1% in 2020 to 18 ± 3% in 2021, reflecting the inverse relationship between yield and protein driven by inter-annual EP variation (Table 3.7). Protein increased consistently with N rate, from 13 ± 2% at 0 kg N ha^{-1} to 16 ± 3% at 168 kg N ha^{-1} (Table 3.7).

Among CC types, pea was the only treatment that significantly increased protein relative to fallow (RR = 107%, 7% gain; $p < 0.05$; Fig. 3.5), with a mean of 15.1% compared to 14.1% under fallow (Table 3.7). This response was consistent across years (year × CC: $F = 1.2$, $p = 0.22$; Fig. 3.6). All other CC types were not significantly different from fallow (Fig. 3.5).

When CC treatments were pooled into a single CC category for a system-level comparison, the CC system effect did not reach significance ($F = 3$, $p = 0.06$), confirming that the protein benefit of CC as a whole was not distinguishable from fallow and was driven primarily by pea.

Table 3.6. Fixed-effects ANOVA for grain protein concentration with effects of year, CC treatment, N rate, and interactions ($\alpha = 0.05$).

Effect	**df**	**F value**	**Pr(>F)**
Year	4	119.8	<0.05
CC	5	18.2	<0.05
N rate	3	776.7	<0.05
Year × CC	20	1.2	0.22
Year × N rate	12	35.3	<0.05
CC × N rate	15	1	0.45
Year × CC × N rate	60	0.9	0.69

Table 3.7. Mean grain protein concentration (%) by CC treatment, crop year, and N rate, averaged across the other two factors. Median and SD describe distribution and spread. Fallow listed first within the CC block; remaining treatments in descending order of mean protein.

Factor	**Level**	**Mean (%)**	**Median (%)**	**SD (%)**
CC treatment	Fallow	14.1	14.2	2.4
	Legume Mix	15	14.7	3
	Pea	15.1	15.1	2.8
	All	14.5	13.8	2.9
	Brassica Mix	14.1	13.8	2.6
	Root Mix	14.1	13.9	2.8
	Grass Mix	13.9	13.2	2.5
Year	2020	11.8	11.6	0.9
	2021	18.1	18.5	2.7

Table 3.7 continued

Factor	Level	Mean (%)	Median (%)	SD (%)
	2022	14.7	14.6	1.5
	2024	13.7	13.9	1.7
	2023	13.6	14	2.2
N rate (kg N ha^{-1})	0	12.5	12	1.8
	56	13.5	13.1	2.3
	112	15.3	14.9	2.6
	168	16.3	16	2.7

Figure 3.5. Protein response ratio (RR) for individual CC averaged across the 2020–2024 period. Points represent the mean response

relative to the fallow control (indicated by the dashed red line at RR = 1), and error bars indicate 95% confidence intervals at α = 0.05.

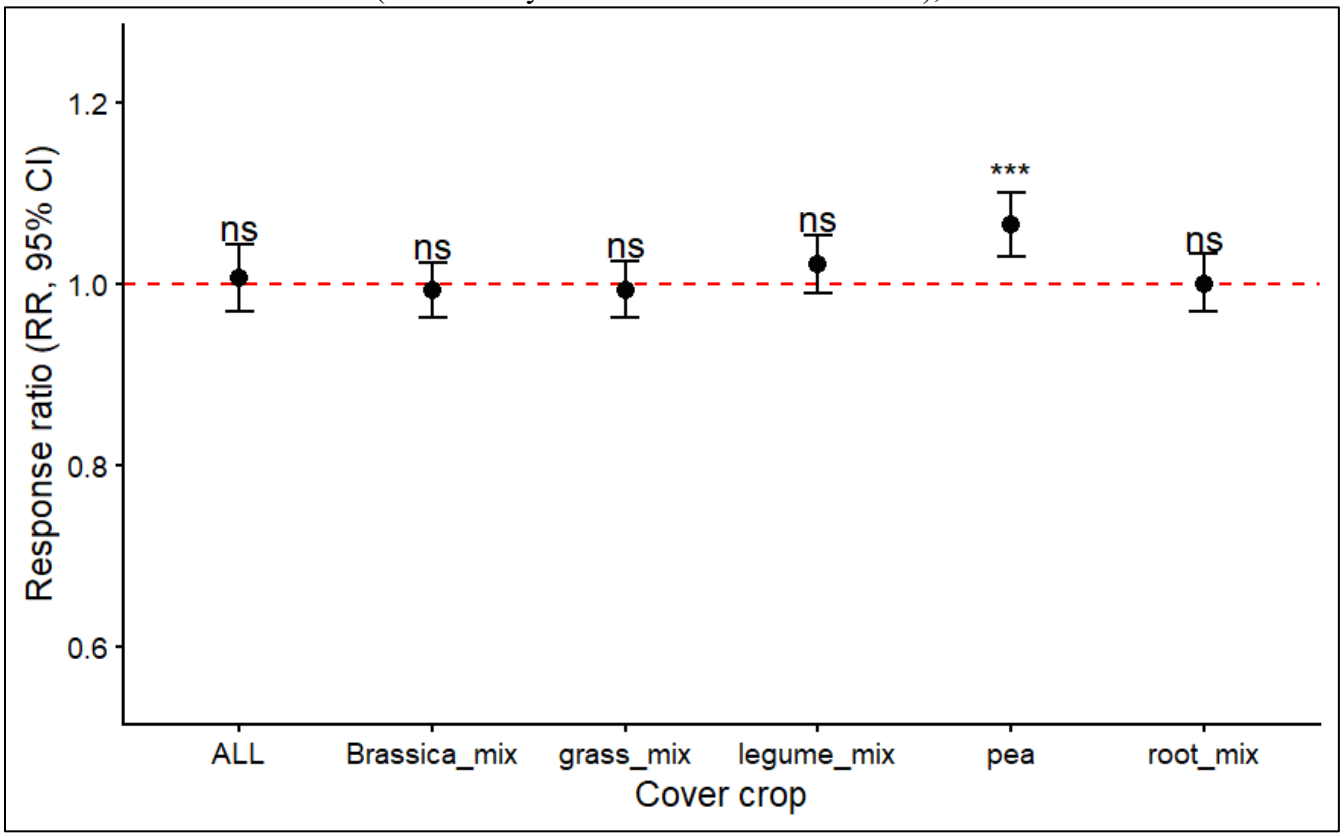
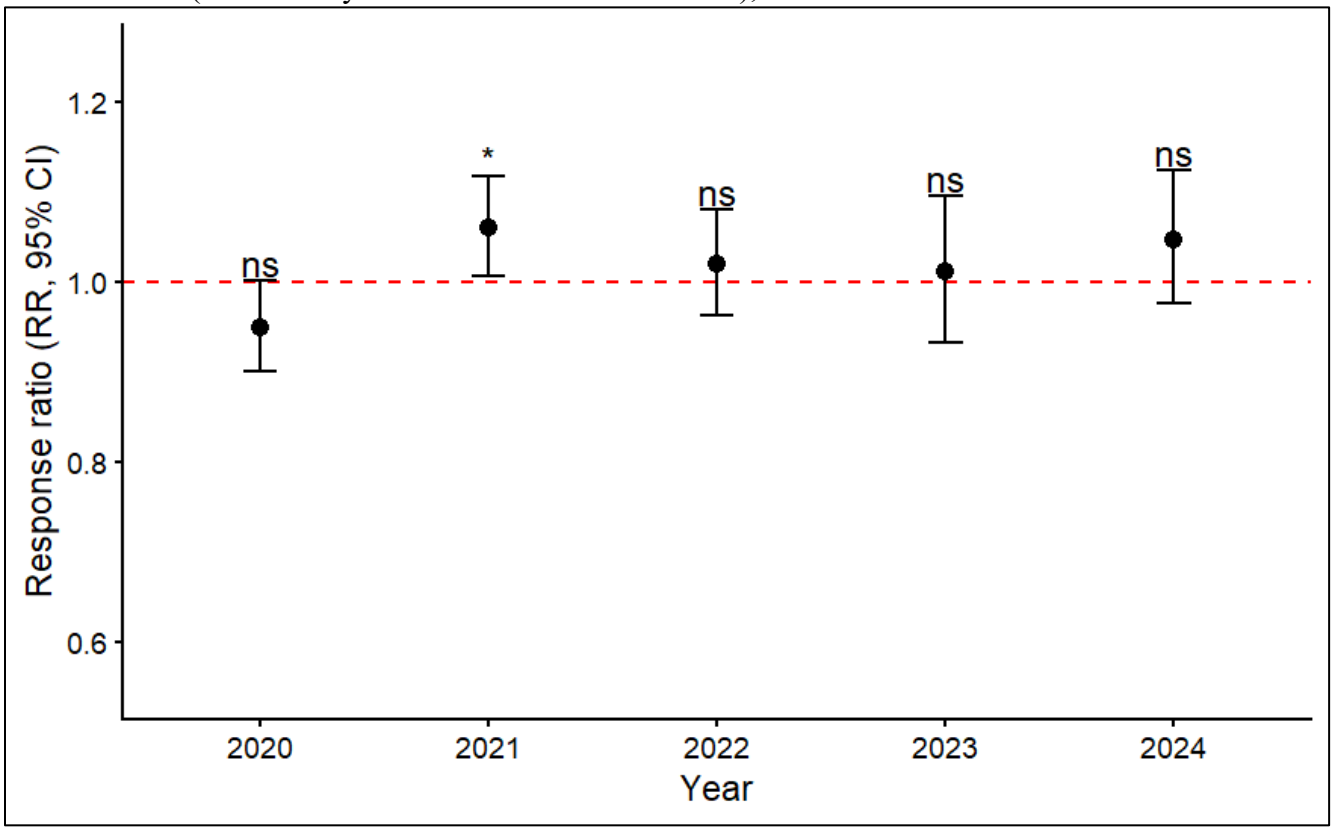


Figure 3.6. Protein response ratio (RR) for CC averaged from the 2020–2024 period. Points represent the mean response relative to the

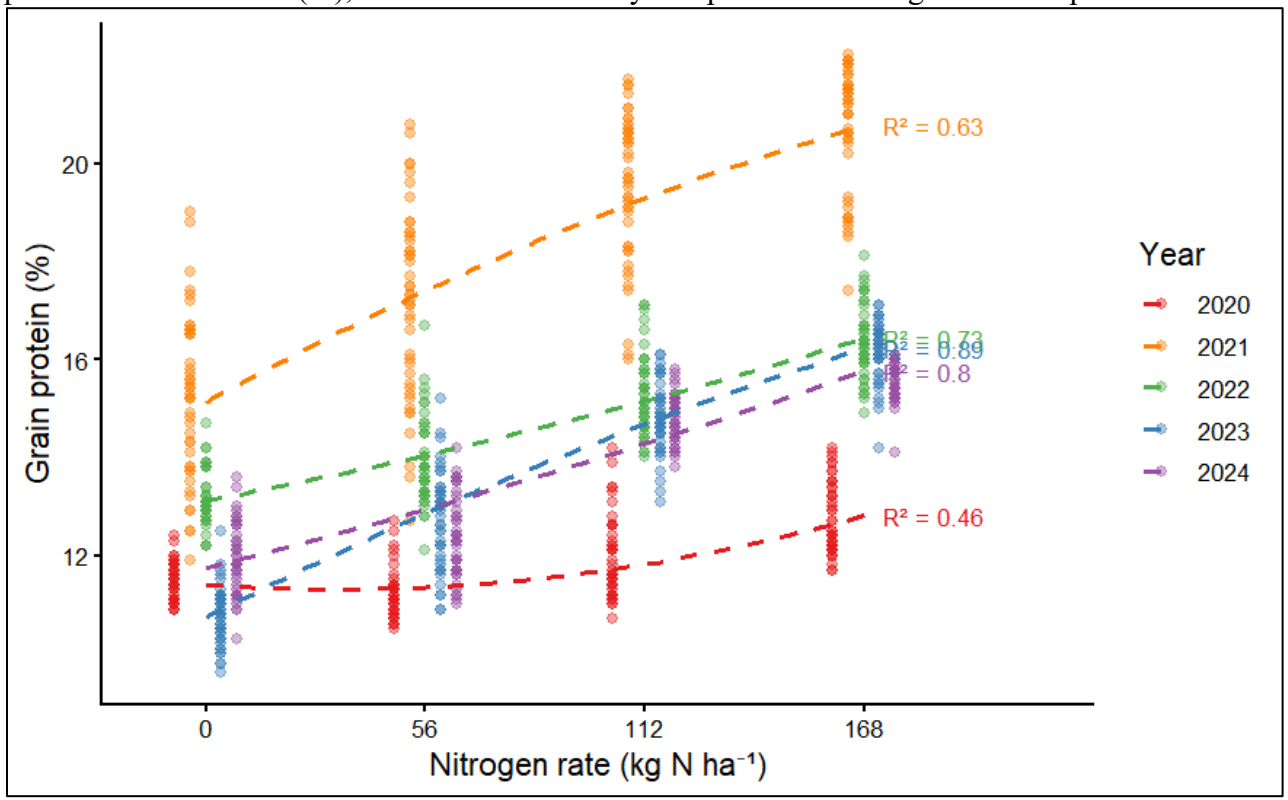
fallow control (indicated by the dashed red line at RR = 1), and error bars indicate 95% confidence intervals at α = 0.05.



3.2.6 Nitrogen and year effects on grain protein

Grain protein increased consistently with N rate across all years, from 12.5 ± 1.8% at 0 kg N ha^{-1} to 16.3 ± 2.7% at 168 kg N ha^{-1} (Table 3.7; Fig. 3.7). The magnitude of this response varied by year (year × N rate: $F = 35.3$, $p < 0.05$; Table 3.6), with steeper protein–N relationships in years with lower EP. The highest protein concentrations occurred in 2021 (18.1 ± 2.7%), the lowest-yielding and driest year (EP = 74 mm), while 2020 had the lowest protein (11.8 ± 0.9%), the highest-EP year (236 mm), consistent with a yield dilution effect.

Figure 3.7. Annual grain protein response to nitrogen fertilizer rates across five years (2020–2024). Points represent individual plot grain protein concentrations (%), and solid lines show year-specific linear regressions of protein on N rate.



3.2.7 Agronomic nitrogen use efficiency (ANUE)

Agronomic nitrogen use efficiency was significantly affected by year, CC type, and N rate (Table 3.9). Year had the strongest effect ($F = 40.6$, $p < 0.05$), followed by N rate ($F = 22.4$, $p < 0.05$) and CC type ($F = 4.7$, $p < 0.05$). Significant two-way interactions were detected for year × CC ($F = 1.6$, $p < 0.05$), year × N rate ($F = 9.8$, $p < 0.05$), and CC × N rate ($F = 2.0$, $p < 0.05$), indicating that ANUE responses to N differed among CC types and varied across years. The three-way interaction was not significant ($p = 0.98$).

Among individual CC treatments, pea showed the smallest ANUE reduction relative to fallow (−20%) and was the only treatment not significantly different from fallow (Fig. 3.8). All other CC treatments were significantly lower than fallow: brassica mix (−27%), root mix (−26%), grass mix (−34%), legume mix (−42%), and All (−46%) (all $p < 0.05$; Fig. 3.8)

Agronomic nitrogen use efficiency was highest at 56 kg N ha^{-1} and declined at higher N rates in all years and under both CC and fallow, indicating diminishing N use efficiency with increasing fertilizer input (Table 3.8). In most year × N rate combinations, fallow ANUE exceeded CC ANUE, with the largest differences in high-EP years. In 2023 (EP = 175 mm), fallow ANUE at 56 kg N ha^{-1} was 69% compared to 49% under CC; in 2020 (EP = 236 mm), fallow was 44% compared to 20% under CC (Table 3.8). Differences narrowed at higher N rates and in lower-EP years. In 2021 (EP = 74 mm), the driest year, ANUE was minimal under both systems at all N rates (fallow: 8–13%; CC: 2–9%), confirming that water availability was the primary constraint on N use efficiency in this dryland system.

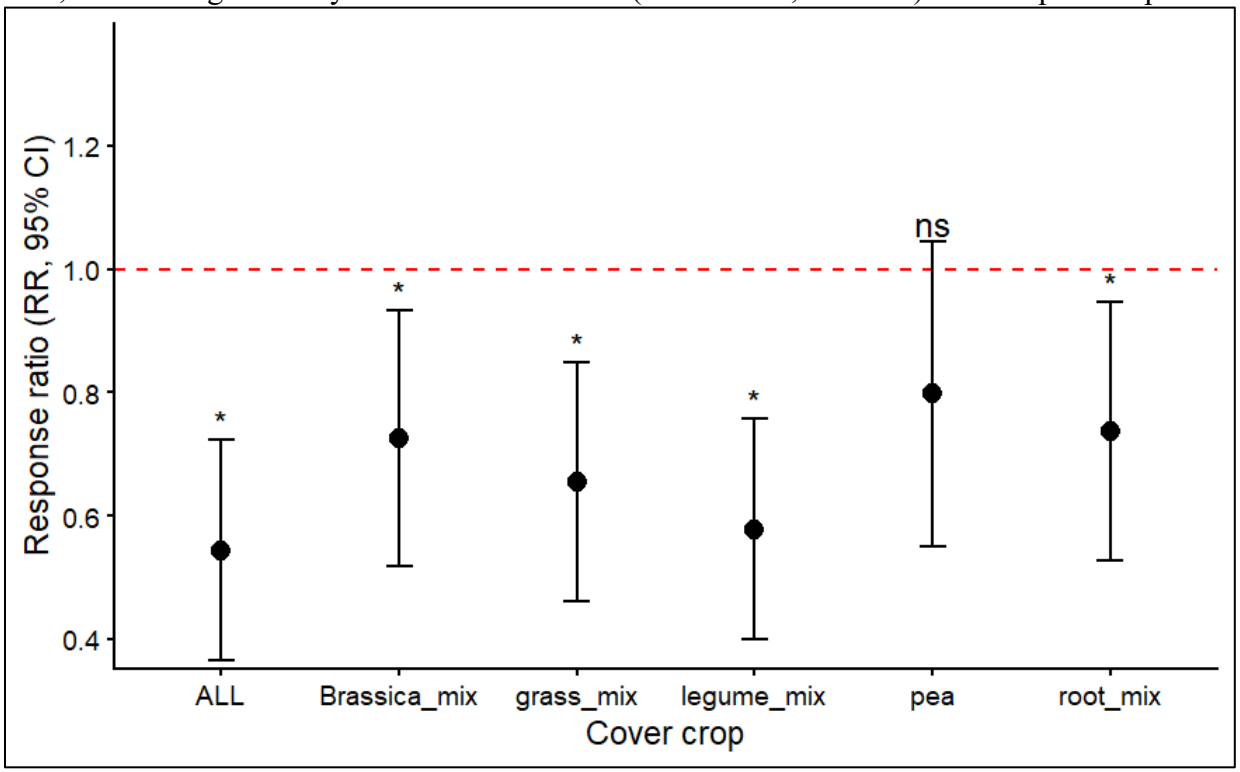
Table 3.8. Comparison of ANUE between CC and fallow across N rates (56, 112, and 168 kg N ha^{-1}) for each year from 2020 to 2024. Bolded values indicate the highest ANUE within each year, between N rates.

	2020		**2021**		**2022**		**2023**		**2024**	
N rate (kg N ha^{-1})	**Fallow**	**CC**	**Fallow**	**CC**	**Fallow**	**CC**	**Fallow**	**CC**	**Fallow**	**CC**
56	44	20	13	9	17	5	69	49	22	18
112	38	24	8	7	9	8	40	35	19	21
168	30	22	9	2	13	4	42	23	16	14

Table 3.9. Fixed-effects ANOVA for ANUE with effects of year, N rate, CC type, and interactions ($\alpha = 0.05$).

Effect	**df**	**F value**	**p**
Year	4	40.6	<0.05
CC	5	4.7	<0.05
N rate	2	22.4	<0.05
Year × CC	20	1.6	<0.05
Year × N rate	8	9.8	<0.05
CC × N rate	10	2	<0.05
Year × CC × N rate	40	0.6	0.98

Figure. 3.8. Mean response ratio (RR = CC ANUE / fallow ANUE) for each CC treatment averaged across all five crop years (2020–2024) and three N rates (56, 112, and 168 kg N ha^{-1}). Percentage labels indicate the mean ANUE difference relative to fallow. Points represent treatment means; error bars indicate 95% confidence intervals. The dashed red line denotes RR = 1 (parity with fallow). * $p < 0.05$; ns = not significantly different from fallow (Fisher LSD, $\alpha = 0.05$). n = 4 replicates per treatment per year.



CHAPTER FOUR: SOIL HEALTH RESPONSES TO COVER CROPS IN DRYLAND CROPPING SYSTEMS

4.1 Abstract

Soil health responses to cover crops (CC) in dryland settings, particularly under semi-arid conditions, where limited precipitation may constrain biological and physical soil improvements, are not fully explored. The responses of six CC treatments and a fallow control, under two nitrogen fertilizer rates (0 and 112 kg N ha^{-1}), on five soil health indicators were evaluated at two depths (0–5 cm and 5–10 cm) at Huntley, Montana.

Soil depth was the dominant factor structuring wet aggregate stability and total carbon, with both properties substantially greater at the surface than at depth. Neither CC treatment nor N rate significantly affected total carbon, plant-available water, field-saturated hydraulic conductivity, or substrate-induced respiration. Wet aggregate stability was likewise unresponsive to CC and N treatments under unfertilized conditions; however, at the 0–5 cm depth under 112 kg N ha^{-1}, four of the six CC treatments: Pea, Root Mix, Grass Mix, and Brassica Mix showed significantly higher aggregate stability than fallow, indicating that surface aggregation responded to cover crops only when nitrogen was applied. Field-saturated hydraulic conductivity was numerically higher under the Grass Mix than fallow, but high variability across all treatments shows no statistically significant differences.

Overall, five years of CC management produced few consistent or statistically detectable improvements in the soil health indicators measured in this study, the main exception being a

nitrogen-dependent increase in surface aggregate stability. These results suggest that the duration of CC management and moisture conditions was generally insufficient to produce measurable changes in soil physical and chemical properties, and that longer-term monitoring will be necessary to detect meaningful soil health responses under dryland cover cropping.

4.2 Results and discussion

4.2.1 Aggregate stability

Wet aggregate stability (WAS, %) ranged from 0.2 to 4.4% across all treatments and depths (Table 4.1). Soil depth dominated the variation; for example, subsurface (5–10 cm) WAS was approximately 12× higher than surface (0–5 cm) WAS across all CC treatments and N rates ($F = 346.8$, $p < 0.05$; Table 4.2). In the full ANOVA, depth was the only factor with a significant main effect; CC treatment, N rate, and all interactions, including the three-way CC × N × Depth term, were non-significant.

When CC effects were quantified relative to fallow using response ratios (RR = 100 × CC ÷ fallow), no CC treatment differed significantly from fallow at either depth under 0 kg N ha^{-1}, nor at 5–10 cm under 112 kg N ha^{-1} (Fig. 4.1). However, at 0–5 cm under 112 kg N ha^{-1}, four of the six CC treatments (Pea, Root Mix, Grass Mix, and Brassica Mix) had significantly higher WAS than fallow, with response ratios of approximately RR = 160% (60% gain), 180% (80% gain), 170% (70% gain), and 190% (90% gain), respectively (all $p < 0.05$; Fig. 4.1). These large ratios partly reflect the very low fallow surface WAS baseline at 112 kg N ha^{-1} (0.2%), against

which modest absolute increases produce large proportional differences. Legume Mix and All did not differ significantly from fallow at this depth and N rate.

This pattern indicates that although depth was the dominant driver of WAS in absolute terms, CC effects on surface-soil aggregate stability emerged only with N fertilization. Under unfertilized (0 N) conditions, no CC treatment improved surface WAS over fallow, suggesting that CC residue alone was insufficient to enhance surface aggregation without supplemental N.

Table 4.1. Wet aggregate stability (WAS, %; Mean ± SD) of the 1–2 mm aggregate size fraction at 0–5 cm and 5–10 cm soil depths by cover crop treatment and nitrogen rate.

Treatment	**Overall CC mean**	**Depth: 0–5 cm**	**Depth: 5–10 cm**	**0–5 cm | N = 0**	**0–5 cm | N = 112**	**5–10 cm | N = 0**	**5–10 cm | N = 112**
All	2.2 ± 2.2	0.3 ± 0.1	4.1 ± 1.5	0.3 ± 0.1	0.3 ± 0.0	4.0 ± 1.6	4.1 ± 1.7
Brassica Mix	2.2 ± 2.1	0.4 ± 0.2	3.9 ± 1.5	0.4 ± 0.2	0.5 ± 0.0	3.8 ± 1.5	4.1 ± 1.7
Fallow	2.3 ± 2.2	0.3 ± 0.1	4.3 ± 1.0	0.3 ± 0.1	0.2 ± 0.0	4.1 ± 1.1	4.5 ± 1.0
Grass Mix	2.3 ± 2.3	0.4 ± 0.1	4.3 ± 1.4	0.3 ± 0.1	0.4 ± 0.1	4.3 ± 1.6	4.3 ± 1.4
Legume Mix	1.9 ± 2.0	0.3 ± 0.1	3.5 ± 1.7	0.3 ± 0.1	0.3 ± 0.1	3.9 ± 1.8	3.0 ± 1.8
Pea	2.3 ± 2.2	0.3 ± 0.2	4.2 ± 1.3	0.3 ± 0.1	0.4 ± 0.2	3.9 ± 1.6	4.5 ± 1.2
Root Mix	2.2 ± 2.1	0.4 ± 0.1	4.1 ± 1.3	0.3 ± 0.1	0.4 ± 0.1	4.1 ± 1.4	4.2 ± 1.3

Table 4.2. ANOVA for Aggregate Stability with effects of Depth, N rate, Treatment (Fallow (n=16) vs CC (n=96)), and interactions (α = 0.05).

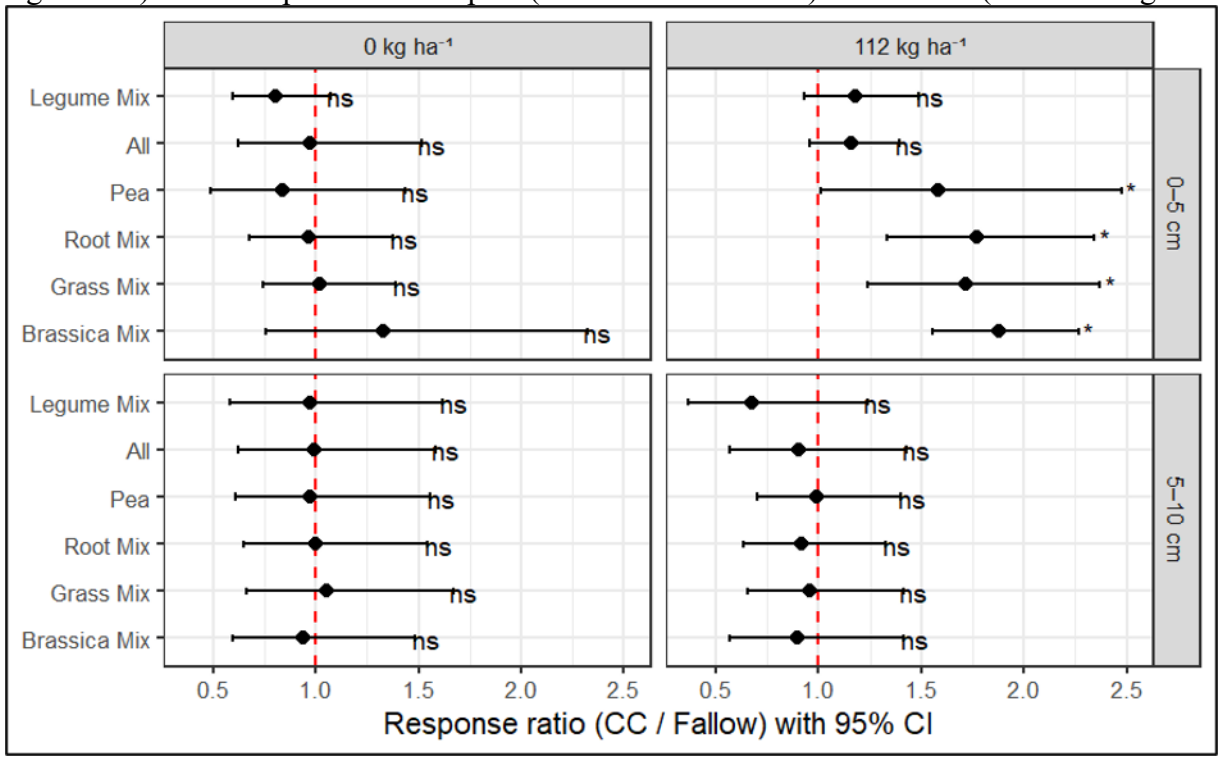
Variables	**Df**	**F-value**	**P_Value**
Depth	1	14.2	<0.05

Table 4.2 continued

Variables	**Df**	**F-value**	**P_Value**
N rate	1	6.0	<0.05
Treatment	5	1.5	0.2
Depth:N rate	1	15.1	<0.05
Depth:Treatment	5	0.7	0.63
N rate:Treatment	5	0.5	0.77
Depth:N rate:Treatment	5	0.2	0.97

Figure 4.1. Response ratios (RR) of wet aggregate stability under different CC, N rate, and soil depth. Points represent mean response ratios, and error bars indicate 95% confidence intervals. The vertical dashed red line at 1 represents no difference from fallow. Values above 1 indicate an increase relative to fallow, while values below 1 indicate a decrease. Significance indicates comparisons of each cover crop treatment with fallow within each depth and nitrogen level, based on separate ANOVA models (* = significant; ns = not

significant). Panels represent soil depths (0–5 cm and 5–10 cm) and N rates (0 and 112 kg N ha^{-1}).



4.2.2 Soil carbon

Soil total carbon (TC) ranged from 0.5 ± 0.1% to 0.7 ± 0.2% at 5–10 cm and from 0.9 ± 0.1% to 1.1 ± 0.2% at 0–5 cm across all treatments and N rates (Table 4.3). Total carbon was significantly influenced by sampling depth ($F = 138.19$, $p < 0.05$), with substantially higher concentrations in 0–5 cm than in 5–10 cm (Tables 4.3 and 4.4). In contrast, neither N rate ($F = 0.40$, $p = 0.53$) nor CC treatment ($F = 1.04$, $p = 0.41$) significantly affected TC, and no interaction term was significant (all $p \geq 0.58$; Table 4.4). In the response ratio analysis, no CC treatment differed significantly from fallow at either depth or N rate, with all response ratios close to 100, overlapping confidence intervals (Fig. 4.2), consistent with the ANOVA results.

Overall, TC at this site was structured primarily by depth and N rate, with no detectable effect of CC or aggregate stability over the study period. This indicates that the cumulative residue inputs from CC over five cropping cycles were insufficient to produce a measurable change in TC relative to fallow at this site.

Table 4.3. Soil total carbon (TC, %; Mean ± SD) at 0–5 cm and 5–10 cm soil depths by cover crop treatment and nitrogen rate.

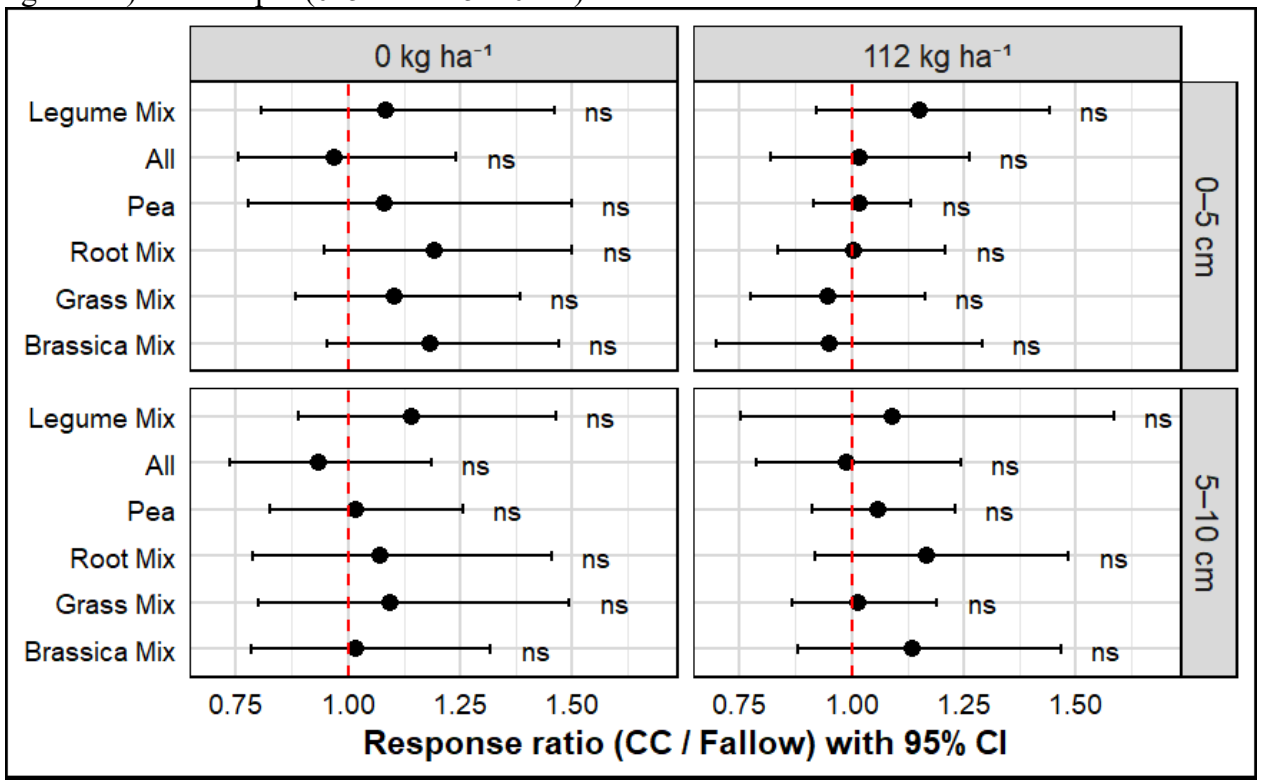
Treatment	0–5 cm | 0 N	0–5 cm | 112 N	5–10 cm | 0 N	5–10 cm | 112 N
Fallow	0.9 ± 0.2	1.0 ± 0.1	0.6 ± 0.1	0.6 ± 0.1
Pea	0.9 ± 0.2	1.0 ± 0.0	0.6 ± 0.1	0.6 ± 0.1
Brassica Mix	1.0 ± 0.1	0.9 ± 0.3	0.6 ± 0.1	0.7 ± 0.2
Grass Mix	1.0 ± 0.1	0.9 ± 0.2	0.6 ± 0.2	0.6 ± 0.1
Legume Mix	1.0 ± 0.2	1.1 ± 0.2	0.7 ± 0.1	0.7 ± 0.2
Root Mix	1.0 ± 0.1	1.0 ± 0.2	0.6 ± 0.2	0.7 ± 0.1
All	0.9 ± 0.1	1.0 ± 0.2	0.5 ± 0.1	0.6 ± 0.1

Table 4.4. Analysis of variance (ANOVA) for soil total carbon showing the effects of soil depth, nitrogen rate (N rate), cover crop treatment (CC), and their interactions (α = 0.05).

Variables	Df	F-value	P_value
Depth	1	138.19	<0.05
N rate	1	0.4	0.53
Treatment	6	1.04	0.41
Depth:N rate	1	0.15	0.7
Depth:Treatment	6	0.05	1
N rate:Treatment	6	0.42	0.86
Depth:N rate:Treatment	6	0.8	0.58

Figure 4.2. Response ratios (RR = CC ÷ Fallow) of soil total carbon under different cover crop treatments, soil depths, and N rates. Points represent mean response ratios; error bars indicate 95% confidence intervals. The vertical dashed red line at RR = 1 indicates no difference from fallow. All CC treatments overlapped RR = 1 at both depths and N rates (ns = not significant), Panels: N rate (0 vs. 112

kg N ha⁻¹) × soil depth (0–5 cm vs. 5–10 cm).



4.2.3 Field-saturated hydraulic conductivity (Kfs)

Field-saturated hydraulic conductivity (Kfs) ranged from 2.4 ± 2.1 cm h^{-1} under fallow to 8.3 ± 7.9 cm h^{-1} under the Grass Mix (Table 4.5). No CC treatment differed significantly from fallow in pairwise comparisons (all $p > 0.16$; Table 4.6), indicating that CC had no detectable effect on Kfs at this site. Although response ratios relative to fallow were numerically above 100 for most CC treatments (Fig. 4.3), variability was high across all treatments, standard deviations frequently approached or exceeded treatment means, and all confidence intervals overlapped fallow. This high variability, which is characteristic of single-ring infiltration measurements in the field (METER Group, 2021; Reynolds, 1990), substantially limited the statistical power to detect treatment differences.

Table 4.5. Field-saturated hydraulic conductivity (Kfs, cm h^{-1}; Mean ± SD) for cover crop treatments.

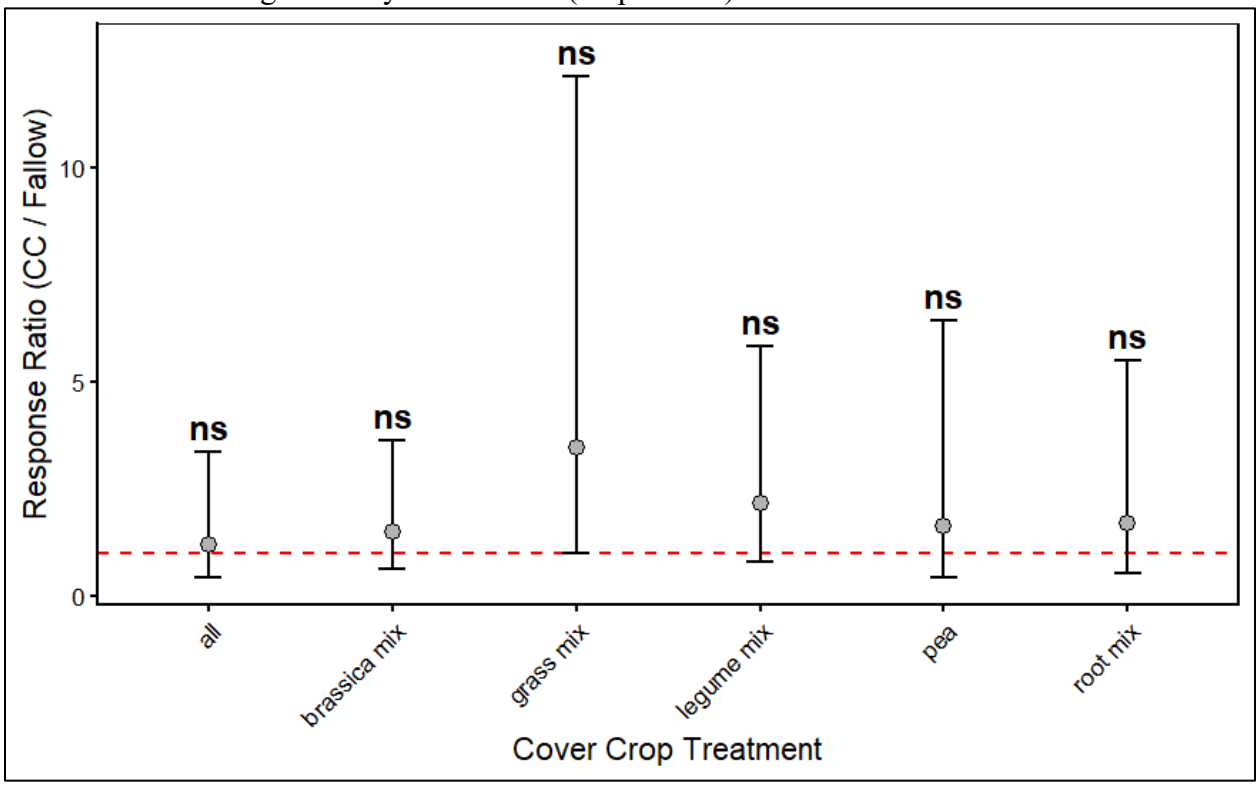
Treatment	Mean ± SD
All	2.9 ± 1.8
Brassica Mix	3.6 ± 0.9
Fallow	2.4 ± 2.1
Grass Mix	8.3 ± 7.9
Legume Mix	5.2 ± 2.8
Pea	3.9 ± 4.3
Root Mix	4.1 ± 3.4

Table 4.6. One-way ANOVA comparing each cover crop treatment with fallow for field-saturated hydraulic conductivity (Kfs; α = 0.05).

Comparison	Df	F_Value	P_Value
All vs Fallow	1	0.12	0.74
Brassica Mix vs Fallow	1	1.13	0.33
Grass Mix vs. Fallow	1	2.1	0.2
Legume Mix vs Fallow	1	2.61	0.16
Pea vs Fallow	1	0.4	0.55
Root Mix vs Fallow	1	0.68	0.44

Figure 4.3. Response ratios (RR = CC ÷ Fallow) for field-saturated hydraulic conductivity (Kfs) across cover crop treatments. Points represent mean response ratios with 95% confidence intervals; the vertical dashed line indicates fallow (RR = 1). No Cover Crop

treatment differed significantly from fallow (all $p > 0.16$).



4.2.4 Plant available water

Plant available water (PAW, % vol/vol) ranged from 18.3 ± 6.6 to 24.8 ± 5.6% at 0–5 cm and from 16.2 ± 5.5 to 28.3 ± 27.8% at 5–10 cm across all treatments and N rates (Table 4.7). Plant-available water did not differ significantly with soil depth, N rate, CC treatment, or any interaction (all $p > 0.54$; Table 4.8), indicating that neither cover cropping nor N management altered plant available water under the conditions of this study. Response ratios relative to fallow were close to 100 with overlapping confidence intervals across all treatments, depths, and N rates (Fig. 4.4), consistent with the ANOVA results. Variability was high across treatments, with high standard deviations, most extreme at 5–10 cm under the Legume Mix (28.3 ± 27.8%). Overall, PAW was insensitive to CC type and N rate at both soil depths over the study period.

Table 4.7. Plant available water (PAW, % vol/vol, i.e., $cm^3\ cm^{-3} \times 100$; Mean ± SD) at 0–5 cm and 5–10 cm soil depths by cover crop treatment and nitrogen rate. n = 4 per cell.

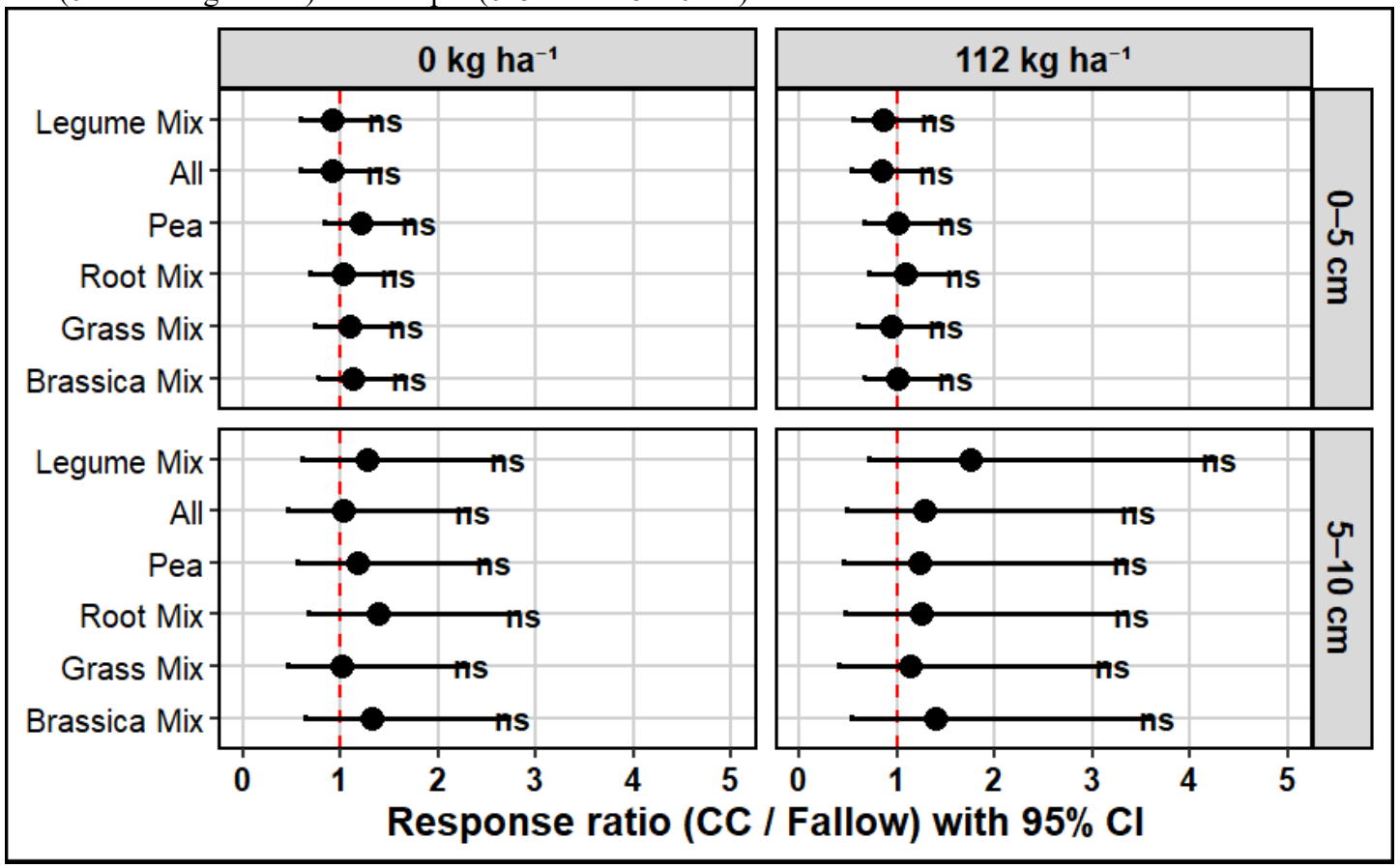
Treatment	0–5 cm | 0 N	0–5 cm | 112 N	5–10 cm | 0 N	5–10 cm | 112 N
Fallow	20.6 ± 2.6	21.7 ± 3.2	19.4 ± 7.4	16.2 ± 5.5
Pea	24.8 ± 5.6	22.0 ± 5.4	22.8 ± 12.9	20.1 ± 7.7
Brassica Mix	23.2 ± 5.8	22.0 ± 1.9	25.5 ± 13.3	22.7 ± 11.1
Grass Mix	22.5 ± 6.3	20.3 ± 5.8	19.8 ± 3.2	18.3 ± 2.8
Legume Mix	18.8 ± 6.1	18.8 ± 6.2	24.7 ± 13.8	28.3 ± 27.8
Root Mix	21.2 ± 8.0	23.5 ± 12.5	26.8 ± 15.0	20.2 ± 6.5
All	18.8 ± 6.8	18.3 ± 6.6	20.1 ± 9.7	20.9 ± 10.1

Table 4.8. Analysis of variance (ANOVA) for plant available water (PAW) showing the effects of soil depth, nitrogen rate (N rate), cover crop treatment (CC), and their interactions ($\alpha = 0.05$).

Source	df	F-value	p-value
Depth	1	0.13	0.72
N rate	1	0.38	0.54
CC treatment	6	0.49	0.81
Depth × N rate	1	0.13	0.71
Depth × CC	6	0.6	0.72
N rate × CC	6	0.11	0.99
Depth × N rate × CC	6	0.18	0.98

Figure 4.4. Response ratios (RR = CC ÷ Fallow) of plant available water (PAW) under different cover crop treatments, soil depths, and N rates. Points represent mean response ratios; error bars indicate 95% confidence intervals. The vertical dashed red line at RR = 1 indicates no difference from fallow. All CC treatments overlapped RR = 1 at both depths and N rates (ns = not significant), Panels: N

rate (0 vs. 112 kg N ha⁻¹) × soil depth (0–5 cm vs. 5–10 cm).



4.2.5 Substrate-induced respiration

Substrate-induced respiration (SIR, μg CO_2-C g^{-1} h^{-1}) measured at 24 hours ranged from 1.14 ± 0.81 to 2.75 ± 0.48 across all treatments, depths, and N rates (Table 4.9). Soil depth was the only significant factor in the ANOVA ($F = 9.56$, $p < 0.05$), with higher respiration at 0–5 cm (mean 2.30) than at 5–10 cm (mean 1.58; Table 4.10). Neither N rate ($F = 0.09$, $p = 0.76$) nor CC treatment ($F = 0.61$, $p = 0.72$) significantly affected SIR, and no interaction term was significant (all $p \geq 0.17$; Table 4.10).

In the response ratio analysis, all treatments fell close to fallow (RR between 65% and 123%), with confidence intervals overlapping 100 in every depth × N rate combination (Fig. 4.5), consistent with the absence of CC and N rate effects in the ANOVA. The largest numerical departures from fallow were a modest elevation under the All and Pea at 0–5 cm (RR ≈ 120%) and a reduction under Pea at 5–10 cm (RR ≈ 65%), but none were statistically distinguishable from fallow.

Overall, SIR was structured primarily by soil depth, with greater microbial respiration near the surface, and was not detectably altered by CC type or N rate over the study period. The relatively weak depth effect for SIR ($F = 9.56$) compared with that for aggregate stability ($F = 346.8$) or total carbon ($F = 138.19$) indicates that microbial activity was less strongly stratified by depth than were the physical and chemical soil properties.

Table 4.9. Substrate-induced respiration (SIR, µg CO_2-C g^{-1} h^{-1}; 24-hour rate; Mean ± SD) at 0–5 cm and 5–10 cm soil depths by cover crop treatment and nitrogen rate.

Treatment	**0–5 cm | 0 N**	**0–5 cm | 112 N**	**5–10 cm | 0 N**	**5–10 cm | 112 N**
Fallow	2.30 ± 0.40	2.10 ± 0.58	1.75 ± 0.52	1.80 ± 0.56
Pea	2.75 ± 0.48	2.45 ± 0.99	1.14 ± 0.81	1.31 ± 0.31
Brassica Mix	2.17 ± 0.27	1.85 ± 1.06	1.78 ± 0.26	1.53 ± 0.28
Grass Mix	2.32 ± 0.70	2.01 ± 0.82	1.60 ± 0.18	1.46 ± 0.12
Legume Mix	2.42 ± 0.81	2.01 ± 0.65	1.79 ± 0.30	1.42 ± 0.91
Root Mix	2.29 ± 0.43	2.21 ± 0.26	2.10 ± 0.34	1.38 ± 0.12
All	2.71 ± 0.91	2.58 ± 0.18	1.47 ± 0.16	1.60 ± 0.39

Table 4.10. Analysis of variance (ANOVA) for substrate-induced respiration (SIR, 24-hour rate) showing the effects of soil depth, nitrogen rate (N rate), cover crop treatment (CC), and their interactions ($\alpha = 0.05$).

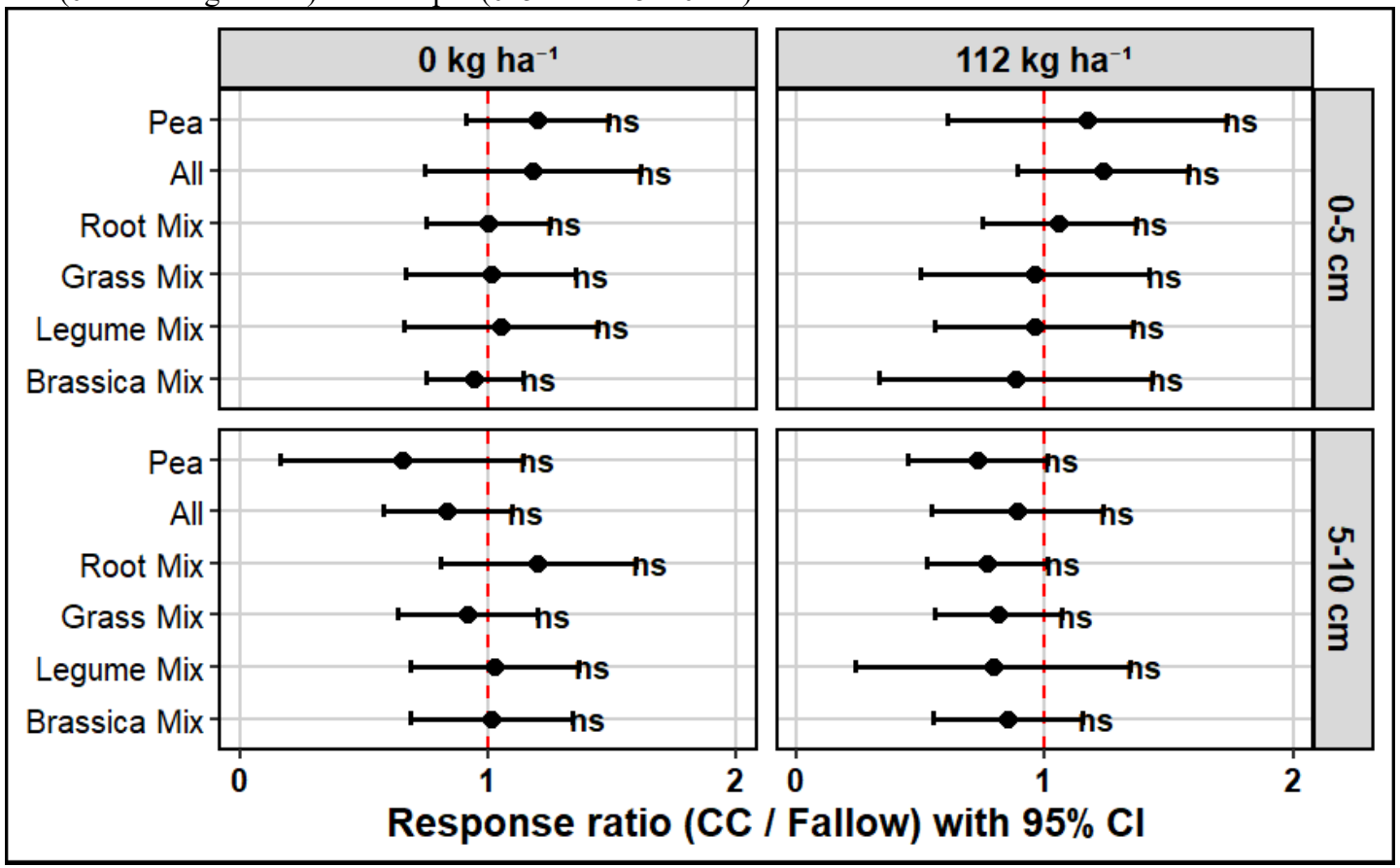
Source	**df**	**F-value**	**p-value**
Depth	1	9.56	<0.05
N rate	1	0.09	0.76
CC treatment	6	0.61	0.72
Depth × N rate	1	0.2	0.66

Table 4.10 continued

Source	df	F-value	p-value
Depth × CC	6	1.54	0.17
N rate × CC	6	0.09	1
Depth × N rate × CC	6	0.38	0.89

Figure 4.5. Response ratios (RR = CC ÷ Fallow) of substrate-induced respiration (SIR) under different cover crop treatments, soil depths, and N rates. Points represent mean response ratios; error bars indicate 95% confidence intervals. The vertical dashed red line at RR = 1 indicates no difference from fallow. All CC treatments overlapped RR = 1 at both depths and N rates (ns = not significant), Panels: N

rate (0 vs. 112 kg N ha⁻¹) × soil depth (0–5 cm vs. 5–10 cm).



CHAPTER FIVE: DISCUSSION AND CONCLUSIONS

5.1 Framing the Discussion: Environment as the Dominant Context

Before interpreting individual treatment effects on yield, it is important to acknowledge the structural reality revealed by the mixed-effects model: the field × year interaction, capturing the combined influence of site-specific conditions (two fields) and inter-annual precipitation variability, accounting for 71% of total wheat yield variance in this study. This was far larger than any management factor tested (e.g., CC explained less than 1% of total yield variance). This pattern is consistent with prior work in dryland farming systems, where precipitation is the primary factor controlling wheat productivity (Carr et al., 2021; Hansen et al., 2012), and has been documented across semi-arid wheat systems in the region (Unger and Vigil 1998; Nielsen and Vigil 2010; Miller et al., 2023).

This does not mean management decisions are unimportant. It means that management practices such as CC and N fertilization should be evaluated within the context set by precipitation. Farmers cannot change the weather, but they can adjust input decisions based on expected moisture conditions. Emerging drought early warning systems (DEWS; https://www.drought.gov) may help inform such decisions. This principle runs through every section of this discussion.

5.2 Cover Crop Effects on Wheat Yield Varied with Year

Averaged across the five-year study, CC reduced wheat yield relative to fallow (RR = 78%, 17% loss). This is consistent with reductions reported in dry environments across the Great Plains. Studies reviewed in Table 1.2 show RR values ranging from roughly 68% to 91% (9% to 32% loss) in environments receiving 350 to 500 mm of annual precipitation (Ghimire et al., 2019; Miller et al., 2023; Nielsen & Vigil, 2005). At Huntley, where annual precipitation is generally below 350 mm, soil water depletion by CC during their growth has been identified as a primary driver of reduced water availability for the following wheat crop (Jones et al., 2022; O'Dea et al., 2015; Unger & Vigil, 1998).

The yield response varied substantially by year. In 2021, the lowest-EP year (EP = 74 mm), CC yielded RR = 68% (32% loss) relative to fallow. In 2022, the third-lowest EP year (EP = 94 mm), CC yielded RR = 84% (16% loss). In 2024, despite similarly low EP (76 mm), CC did not reduce yield relative to fallow (RR = 103%, 3% gain; $p = 0.3$). In the two highest-EP years, CC yielded RR = 87% (13% loss) in 2020 (EP = 236 mm) and RR = 74% (26% loss) in 2023 (EP = 175 mm). The pattern, with significant CC losses in both low- and high-EP years but not in 2024, indicates that EP alone does not fully determine the magnitude of the CC yield response in any given year.

Fig. 5.1 places these findings within the broader published literature. Across studies from a range of environments, there is a general positive trend between annual precipitation and the CC response ratio, with wetter environments tending to produce smaller losses, or even gains, in yield following CC. However, the scatter around this trend is wide. Several studies at higher precipitation levels report RR values below 100%, and some studies at lower precipitation report

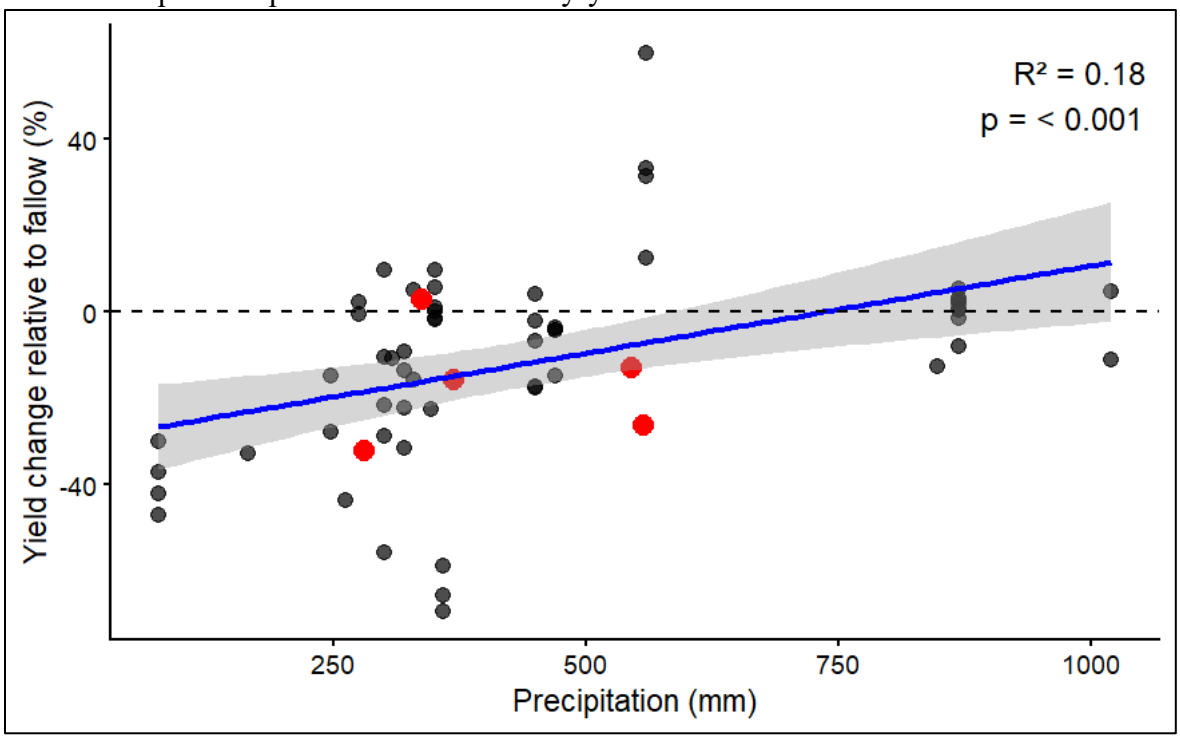
RR values near 100%. The red data points representing the current study fall in the lower-to-moderate precipitation range and sit within the cluster of RR values below or near 100% observed at comparable precipitation in the literature.

This pattern suggests that annual precipitation amount alone is not a reliable predictor of CC performance. Other factors, including seasonal distribution of rainfall, soil water storage, CC species, and termination timing, also shape outcomes (Blanco-Canqui et al., 2013; Miller et al., 2023; Unger & Vigil, 1998). The spread of red points from this study across multiple RR values within a single site illustrates this within-site variability.

For producers and advisors, this means that a simple rule based solely on annual precipitation is not supported by the data from this study or the broader literature. Precipitation is a useful guide, but decisions about CC adoption may need to account for seasonal moisture distribution, soil texture, species selection, and termination timing in addition to total precipitation.

By 2024, yields under most CC treatments had approached or exceeded the fallow baseline. The experimental site has been under the same management since 2016, meaning soils at this site have been under CC management for nearly a decade. The 2024 result may reflect favorable growing conditions that year; whether it also reflects gradual improvements in soil biological activity, N cycling, or organic matter accumulation under longer-term CC management cannot be determined from this study alone. The literature includes reports of smaller yield reductions under longer-term CC management as soil conditions improve (Allen et al., 2011; Blanco-Canqui et al., 2012; Chen et al., 2012). Continued monitoring at this site will be necessary to determine whether the 2024 trend toward yield parity is sustained.

Figure. 5.1. Relationship between annual precipitation and cover crop effects on wheat yield, expressed as percent change relative to fallow, compiled from 17 published studies summarized in Table 1.2. The fitted blue regression line shows the overall trend across published study-year observations ($R^2 = 0.18$, $p < 0.001$), and the shaded region represents the 95% confidence interval of the fitted regression. Red points represent annual values from the current study (2020–2024), while black points represent individual study-year observations from the literature.



5.3 Cover Crop Type Differences in Wheat Yield

Among CC treatments tested, the grass mix and All produced the lowest wheat yields across years on average (RR = 79%, 21% loss; Fig. 3.2). Root mix (RR = 80%, 20% loss), legume mix (RR = 83%, 17% loss), and brassica mix (RR = 84%, 16% loss) all showed significant yield reductions relative to fallow, while pea (RR = 90%, 10% loss) was not significantly different from fallow.

This pattern aligns with functional differences between CC groups documented in the literature (Table 1.2). Grass species generally use more water and produce more biomass than legumes or brassicas, which can result in greater soil water depletion before wheat planting (Miller et al., 2011).

Pea performed relatively well in this study. Legumes can partially offset their negative impact on grain yield by providing N through biological fixation, which provides a higher protein yield of wheat (Miller et al., 2023; Nielsen & Vigil, 2010). For producers in water-limited environments, pea was associated with the smallest mean yield loss (RR = 90%, 10% loss), while the brassica mix and legume mix showed smaller losses than the grass mix and the All treatment. However, all cover crop treatments were associated with significantly lower yields than fallow on average and carried significant yield risk under the conditions of this study.

5.4 N Rate Effects on Wheat Yield Under CC and Fallow

Wheat yield responded positively to N under both CC and fallow, but the response varied by year (Table 3.4; Fig. 3.4). The CC × N rate interaction was not statistically significant in this study ($F = 1.52$, $p = 0.093$), indicating that the yield response to N did not differ systematically between CC and fallow.

Increasing the N rate did not eliminate the CC yield gap in any year. At 0 kg N ha^{-1}, CC remained below fallow in most years (RR = 76%, 73%, 90%, 73%, and 102% for 2020–2024). At 112 kg N ha^{-1}, RR changed little and was not consistent across years (RR = 87%, 86%, 88%, 73%, and 113% for 2020–2024), and CC treatments generally continued to underperform fallow. This indicates that N limitation alone did not account for the lower CC yields observed in this

study; soil water depletion by CC in the preceding year is a likely contributing factor, consistent with prior work identifying soil moisture as a dominant limitation in dryland CC systems (Jones et al., 2022; Unger & Vigil, 1998).

N response varied by year. In wetter years, yield increased more strongly with N rate under both systems. In drier years, yield differences among N rates were smaller. This pattern indicates that the agronomic value of higher N rates in this system was conditioned on growing-season moisture and that uniform N recommendations across years may not be optimal for variable-precipitation environments.

5.5 Economic Considerations for CC and N Fertilization

Cover crop establishment carries costs including seed, fuel, labor, equipment, and management time, while chemical fallow requires herbicide applications and tillage passes. A general breakeven framing is:

$$Yield\ penalty\ (Mg\ ha-1) \times Wheat\ price\ (\$/Mg)$$
$$\leq Fallow\ cost\ (\$/ha) - CC\ establishment$$

Averaged across five years, wheat yield following CC was approximately 17% lower than fallow. The yield penalty was largest in low-EP years and was not detectable in 2024. Seed cost is a meaningful component of CC establishment, particularly for multi-species mixes, and varies by species and rate. If CC provides measurable soil benefits, CC over the longer term may be beneficial for the farmer, though such benefits were not detected in the five-year window of this study.

An estimate of N fertilization, provided in Table 5.1, was conditioned on EP. In wetter years of this study, 56 kg N ha^{-1} produced the highest net return among rates tested, while 168 kg N ha^{-1} produced a net loss despite higher absolute yield. In drier years, all N rates above 0 produced negative net returns in this analysis.

Returns from both CC and N rate decisions in dryland systems depend on growing-season moisture. In wetter years, moderate N rates (56–112 kg N ha^{-1}) were economically supportable in this study, and CC yield penalties were smaller. In drier years, higher N rates and CC establishment costs were less likely to be recovered through yield gains under the conditions and prices analyzed.

Projected temperature increases of 2.5–3.3°C and up to 5.4°C by 2100 for Montana (Whitlock et al., 2017; Conant et al., 2018) will increase evapotranspiration and may reduce EP even if total precipitation remains stable. Years currently above CC breakeven thresholds may shift below them. Seasonal moisture outlooks from drought early warning systems may help producers condition CC and N decisions on expected conditions.

Table 5.1. Economic analysis of N fertilizer rates based on wheat yield response and urea fertilizer cost (USDA NASS, 2020), urea fertilizer cost from 2020 Montana market prices. The 0 kg N ha^{-1} treatment is baseline, and yield gain equals additional yield relative to this treatment. Income was calculated from yield gain using the 2020 Billings-area wheat price; net return was calculated as income minus fertilizer cost. Wet and dry columns represent average responses under wetter (2020, 2023) and drier (2021, 2022, 2024) conditions in this study.

N Rate (kg/ha)	**Urea Req (kg/ha)**	**Cost ($/ha)**	**Yield Wet (kg/ha)**	**Yield Gain**	**Wet Income ($)**	**Wet Return ($)**	**Yield Dry (kg/ha)**	**Yield Gain**	**Dry Income ($)**	**Dry Return ($)**
0	0	0	1923	0	0	0	1122	0	0	0
56	121.7	43.8	2834	911	75.2	31.4	1284	162	13.4	-30.4
112	243.5	87.7	3209	1286	106.1	18.4	1421	299	24.7	-63
168	365.2	131.5	3260	1337	110.3	-21.2	1304	182	15	-116.5

5.6 EP and Wheat Yield

Wheat yields in this study were strongly associated with EP under both fallow and CC (Table 3.5; Fig. 3.3). Yields following fallow ranged from 1,416 ± 300 kg ha^{-1} in 2021 (EP = 74 mm) to 4,080 ± 359 kg ha^{-1} in 2023 (EP = 175 mm). Yields following CC followed a similar pattern, from 1,013 ± 322 kg ha^{-1} in 2021 to 3,019 ± 430 kg ha^{-1} in 2023, second highest and 3349 ± 388 in 2020 (EP = 236 mm).

Fallow accumulates water in the soil profile during the fallow year, which is then available for the following wheat crop. The absolute yield gap between fallow and CC was largest in the highest-EP years (2020 and 2023), where total productivity was greatest in both systems. In 2024, CC yields were not significantly different from fallow despite low EP, indicating that EP alone does not fully explain CC outcomes and that year-specific factors such as residue carryover, planting date, and cool-season precipitation also contribute. The findings of this study reinforce that EP is a strong driver of wheat productivity at this site, but not a complete predictor of relative CC performance.

5.7 Grain Protein

The five-year mean grain protein in this study was 14 ± 2% (Table 3.7). Year and N rate were the strongest drivers of protein concentration (Table 3.6). The CC × N rate interaction for protein was not statistically significant ($F = 1.0$, $p = 0.45$), indicating that the protein response to N did not differ systematically among CC treatments in this study.

Protein was highest in the driest, lowest-yielding year (2021: 18 ± 3%) and lowest in the wettest, highest-yielding year (2020: 12 ± 1%), consistent with the yield-protein dilution effect. Protein increased with N rate, from 12.5 ± 1.8% at 0 kg N ha^{-1} to 16.3 ± 2.7% at 168 kg N ha^{-1} (Table 3.7).

Among CC treatments, pea was the only treatment to significantly increase protein relative to fallow (RR = 107%, 7% gain; Fig. 3.5). This is consistent with research showing that legume CC can contribute biologically fixed N to the soil, some of which becomes available to the following crop and increases grain N concentration (Zablotowicz et al., 2011).

In the Northern Great Plains wheat market, where high protein content can attract price premiums, the pea result may be practically relevant: the modest yield reduction under pea in this study may be partially offset by grain protein premiums, depending on prevailing market conditions and pea adaptability to the specific region.

5.8 Agronomic N Use Efficiency

Agronomic nitrogen use efficiency was significantly affected by year, CC treatment, and N rate, with significant two-way interactions among all three factors (Table 3.9). The three-way interaction was not significant.

Among individual CC treatments, pea showed the smallest ANUE reduction relative to fallow (RR = 80%, 20% loss) and was the only CC treatment where ANUE was not significantly different from fallow (Fig. 3.8). All other CC treatments resulted in ANUE being significantly lower than fallow: brassica mix (RR = 73%, 27% loss), root mix (RR = 74%, 26% loss), grass mix (RR = 66%, 34% loss), legume mix (RR = 58%, 42% loss), and All (RR = 54%, 46% loss)

(all $p < 0.05$; Fig. 3.8). The relatively larger ANUE reduction under legume mix and All compared to pea may reflect that single-species pea is more consistent in N fixation and release than multi-species mixes where legume contribution is shared across species; this mechanism is not separately tested in this study.

In most year × N rate combinations, fallow ANUE exceeded CC ANUE, with the largest differences at 56 kg N ha^{-1} in the two wetter years (Table 3.8). In 2023, fallow ANUE at 56 kg N ha^{-1} was 69% compared to 49% under CC; in 2020, fallow was 44% compared to 20% under CC. For legume-containing treatments, residue decomposition may have contributed to N availability during the wheat growing season, although the mechanism cannot be confirmed from this study alone. The pattern is consistent with the literature reviewed in Table 1.5, where legume CC most commonly improved N use efficiency at low to moderate N rates, with smaller or absent improvements at high N inputs (Habbib et al., 2017; Hubbard et al., 2013; Zablotowicz et al., 2011).

Differences narrowed at higher N rates and in lower-EP years. In 2021 (EP = 74 mm), ANUE was low under both systems at all N rates (fallow: 8–13%; CC: 2–9%), confirming that water availability was the primary constraint on N use efficiency in this dryland system. ANUE was highest at 56 kg N ha^{-1} and declined at higher rates in all years under both systems, indicating diminishing N use efficiency with increasing fertilizer input. Of the rates tested in this study (0, 56, 112, 168 kg N ha^{-1}), the 56–112 kg N ha^{-1} range gave the highest ANUE under both CC and fallow.

5.9 Soil Health

The findings of this study indicate that despite CC management at this site beginning in 2016, no consistent or statistically significant improvements due to CC were detected across many of the soil health indicators measured: total carbon (TC), field-saturated hydraulic conductivity (Kfs), plant available water (PAW), and substrate-induced respiration. The results across all four indicators point to a common underlying constraint: in water-limited environments like Huntley, CC biomass production is restricted by moisture availability, which in turn limits organic material returned to the soil and constrains the biological and physical processes that drive soil health improvement.

Total carbon did not change significantly under any CC treatment or N rate over the study period. TC is reported here as soil organic carbon following McVay and Khan (2022), who established that inorganic carbon is negligible at this site for depths less than 15 cm. The absence of detectable TC change in this study is consistent with findings from other semi-arid environments reviewed in Table 1.3. Ghimire et al. (2019) reported near-zero TC changes under CC at approximately 470 mm annual precipitation, and Blanco-Canqui et al. (2013) found TC responses in semi-arid soils were small and variable. In a Montana study by Jones et al. (2025), TC in the top 10 cm was approximately 10% greater under an 8-species CC and sole pea CC than fallow after seven years at two semi-arid sites, suggesting that longer management durations under sufficient biomass conditions may eventually produce measurable TC change. Whether such a response develops at this site beyond the current sampling window will require continued monitoring.

Water stable aggregates differed primarily by soil depth in this study, with depth accounting for the dominant share of variation ($F = 346.8$, $p < 0.05$; Table 4.2). Cover crop treatment and N rate did not have significant overall effects in the full ANOVA. Surface-layer (0–5 cm) increases were observed under four CC treatments (Pea, Root Mix, Grass Mix, Brassica Mix) at 112 kg N ha^{-1} compared to fallow (Fig. 4.1), but this pattern was specific to the surface depth and N112 combination and was not present at 0 N or at 5–10 cm. The literature reviewed in Table 1.6 indicates that CC effects on aggregate stability in dry environments are generally small and variable, with the more reliable improvements occurring where biomass production is high enough to substantially increase organic matter inputs (Blanco-Canqui et al., 2013; Biederbeck et al., 1998; Campbell et al., 1993).

Kfs and PAW did not differ significantly between CC treatments and fallow (Tables 4.6, 4.8). Kfs was numerically higher under the grass mix than fallow, but variability across all treatments was high, and confidence intervals overlapped fallow in all pairwise comparisons. High spatial variability in soil hydraulic properties is a documented challenge in semi-arid field studies and is consistent with limited Kfs responses reported by Blanco-Canqui and Jasa (2019). The absence of significant differences in PAW indicates that the yield penalties observed in this study were not associated with detectable changes in soil water storage capacity. This points to termination timing, which directly affects how much soil water is depleted before wheat planting, as a more relevant management lever for managing CC water cost than expected changes in soil hydraulic properties at this site (Miller et al., 2011; Unger and Vigil 1998).

The lack of a cover crop effect on SIR suggests that microbial activity was relatively resilient to differences in CC composition under the environmental conditions of this study.

Similar findings have been reported in semi-arid cropping systems, where limited soil moisture and relatively short CC durations can constrain microbial responses despite changes in residue inputs and plant diversity. The higher SIR observed in the 0–5 cm layer likely reflects greater concentrations of organic residues, root inputs, and microbial biomass near the soil surface. Although some treatments showed numerical increases or decreases relative to fallow, the absence of significant response ratio effects indicates that CC did not consistently alter microbial respiration during the five-year study period.

The integrated picture across these five indicators is consistent: CC management at this site over the study period did not produce statistically detectable improvements in soil chemical, biological, or physical properties. The most likely constraint is biomass limitation under semi-arid conditions rather than management duration alone, given that the site has been under CC since 2016. The findings of this study do not establish that CC cannot improve soil health under different conditions or longer timeframes, but they do not support near-term soil health improvement as a primary justification for CC adoption in environments with comparable climate.

5.10 What This Study Addressed and Open Questions

This study addressed several research gaps identified in the literature review. First, it provided multi-year, replicated, site-specific data on CC and N management interactions at a semi-arid dryland site in Montana, where such data were identified as limited (Unger and Vigil 1998; Carr et al., 2021; Obour et al., 2021). Second, it evaluated CC effects across multiple response variables simultaneously: wheat yield, grain protein, ANUE, TC, aggregate stability, Kfs, and PAW. Third, by placing site-specific findings within the context of broader published

literature (Fig. 5.1), this study illustrated that precipitation variability shapes CC yield outcomes across environments and that a fixed precipitation threshold for CC viability is not supported by the available data.

Several questions remain open. Despite CC management at this site since 2016, no significant soil health improvements were detected during the study period; whether such responses develop over longer timeframes will require continued monitoring. The economic analysis was based on a single wheat price and fertilizer cost scenario; how recommendations shift under different market conditions, and at different scales of seed cost for multi-species mixes, would be worth evaluating in future work. CC termination timing was not independently evaluated and represents a clear priority for future research as a practical tool for reducing the water cost of CC adoption in semi-arid systems. A limitation of this study is that the lack of a CC yield penalty in 2024 cannot be definitively attributed to either favorable seasonal precipitation patterns or cumulative effects of long-term CC management. Additional years of data and direct soil-water measurements would be needed to distinguish among these possibilities.

5.11 Summary and Practical Considerations

The main findings of this study are as follows. On average, CC reduced wheat yield relative to fallow (RR = 83%, 17% loss), but this reduction was not consistent across years. Cover crop reduced wheat yield significantly relative to fallow in all years except 2024, including both the driest and the wettest years. No CC treatment produced consistent, statistically significant improvements in the soil health indicators measured in this study, despite management beginning at this site in 2016. Agronomic nitrogen use efficiency under fallow was

higher than CC in all year × N rate combinations at 56 kg N ha^{-1}, with the largest advantages in wetter years.

For producers in the Huntley area and similar semi-arid environments of the Northern Great Plains, several considerations follow from these findings. Cover crop carried real yield and economic risk in dry years in this study, and risk was greatest with grass-dominated mixtures. Legume- and brassica-based CC were lower risk in this study, and pea showed a small but significant benefit for grain protein that may partially offset yield-based losses through quality premiums under favorable market conditions, where pea is adaptable to local conditions. N rates in the 56–112 kg N ha^{-1} range gave the best combination of yield response and N use efficiency among the rates tested in this study under both CC and fallow; higher rates produced diminishing returns and were not consistently profitable in drier years under the prices analyzed.

The findings of this study do not support broad recommendations against CC adoption in semi-arid dryland systems. They do indicate that management strategies developed in wetter regions cannot be transferred directly to environments comparable to Huntley without adjustment. CC adoption decisions should be informed by local data, realistic yield expectations, and an understanding of how EP variability shapes outcomes year to year. As climate projections for the Northern Great Plains indicate warmer temperatures and potentially altered summer precipitation (Conant et al., 2018; Whitlock et al., 2017), region-specific evidence-based management guidelines for dryland systems in Montana will continue to be relevant.

5.12 Conclusion

This study evaluated the effects of CC and N management on wheat yield, grain protein, agronomic N use efficiency, and soil health in a semi-arid dryland cropping system at Huntley, Montana. The site has been under CC management since 2016, and this study captured five years of agronomic and soil health data within that longer management period.

Growing-season EP was the dominant factor associated with wheat productivity, N response, and CC performance in this study. Management factors such as CC treatment and N rate had statistically significant effects, but their effect sizes were much smaller than the inter-annual variation associated with EP. This indicates that management decisions in this system are best made with realistic expectations and calibrated to seasonal moisture conditions.

N fertilization improved both wheat yield and grain protein across years, but the size of this response depended on growing-season moisture. In dry years, yield responses to N were small, and higher N rates resulted in negative net returns under the prices analyzed. Among the rates tested, the 56–112 kg N ha^{-1} range produced the best combination of yield response and N use efficiency under both CC and fallow. Agronomic nitrogen use efficiency under fallow was higher than CC in most year × N rate combinations at 56 kg N ha^{-1}, with larger advantages in wetter years.

Cover crop reduced wheat yield relative to fallow in this study (RR = 83%, 17% loss on average). The loss was concentrated in low-EP years and was not significant in 2024 despite low EP. Among CC treatments, grass-dominated mixtures carried the largest yield reduction, while legume-based and brassica-based options performed better. Pea was the only CC treatment to

significantly increase grain protein relative to fallow, which may offer producers a modest quality-based economic benefit under favorable market conditions and where pea is adaptable.

No consistent or statistically significant improvements were detected in TC, wet aggregate stability, Kfs, SIR, or PAW across the five-year sampling window of this study, despite CC management beginning in 2016. Semi-arid conditions at this site constrain CC biomass production, which constrains organic material returned to the soil. The findings of this study do not support near-term soil health gain as a primary justification for CC adoption in environments with comparable climate.

Taken together, the findings of this study indicate that under the conditions observed at Huntley over 2020–2024, CC did not provide clear agronomic, soil health, or short-term economic advantages over fallow on average. In wetter years, the CC yield reduction was smaller, and legume-based species offered modest N efficiency and grain protein benefits. The decision to adopt CC in semi-arid dryland systems should be made with realistic expectations, species choices appropriate to local conditions, and conservative N management. As climate variability in the Northern Great Plains continues, region-specific evidence-based management guidelines will remain relevant for producers in dryland systems comparable to this study site.

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APPENDIX: SUPPLEMENTAL FIGURES

Wheat yield

Table S1. Percent change in wheat yield under different cover crop treatments relative to fallow across years. Values are expressed as percent change compared to fallow within each year, and p-values indicate whether the difference between cover crop and fallow yields is statistically significant at $\alpha = 0.05$.

Year	Cover_crop	Mean_CC Kg/ha	Mean_Fallow Kg/ha	% change from fallow	p_value
2020	All	2754	3258	-15	0.07
2020	Brassica_mix	2850	3258	-13	0.12
2020	grass_mix	2696	3258	-17	<0.05
2020	legume_mix	2922	3258	-10	0.19
2020	pea	3180	3258	-2	0.79
2020	root_mix	2767	3258	-15	0.06
2021	All	734	1397	-47	<0.05
2021	Brassica_mix	983	1397	-30	<0.05

Table S1 continued

Year	Cover_crop	Mean_CC Kg/ha	Mean_Fallow Kg/ha	% change from fallow	p_value
2021	grass_mix	887	1397	-36	<0.05
2021	legume_mix	1019	1397	-27	<0.05
2021	pea	1127	1397	-19	<0.05

2021	root_mix	914	1397	-35	<0.05
2022	All	1243	1482	-16	<0.05
2022	Brassica_mix	1386	1482	-6	0.35
2022	grass_mix	1214	1482	-18	<0.05
2022	legume_mix	1196	1482	-19	<0.05
2022	pea	1035	1482	-30	<0.05
2022	root_mix	1308	1482	-12	0.09
2023	All	2529	3597	-30	<0.05
2023	Brassica_mix	2606	3597	-28	<0.05
2023	grass_mix	2656	3597	-26	<0.05
2023	legume_mix	2697	3597	-25	<0.05
2023	pea	3117	3597	-13	<0.05
2023	root_mix	2465	3597	-31	<0.05
2024	All	1598	1550	3	0.73
2024	Brassica_mix	1696	1550	9	0.26
2024	grass_mix	1478	1550	-5	0.58
2024	legume_mix	1586	1550	2	0.78
2024	pea	1739	1550	12	0.16
2024	root_mix	1558	1550	0	0.95

Table S2. Percent change in wheat yield under different cover crop treatments relative to fallow across N rates. Values are expressed as percent change compared to fallow within each nitrogen level, and p-values indicate whether the difference between cover crop and fallow yields is statistically significant at $\alpha = 0.05$.

N_rate Kg/ha	**Cover_crop**	**Mean_CC Kg/ha**	**Mean_Fallow Kg/ha**	**% change from fallow**	**p_value**
0	All	1371	1760	-22	0.08
0	Brassica_mix	1450	1760	-18	0.08

0	grass_mix	1260	1760	-28	<0.05
0	legume_mix	1488	1760	-15	0.16
0	pea	1755	1760	0	0.98
0	root_mix	1295	1760	-26	<0.05
56	All	1764	2188	-19	0.14
56	Brassica_mix	1942	2188	-11	0.34
56	grass_mix	1795	2188	-18	0.12
56	legume_mix	1862	2188	-15	0.21
56	pea	2095	2188	-4	0.78
56	root_mix	1852	2188	-15	0.18
112	All	2044	2510	-19	0.19
112	Brassica_mix	2143	2510	-15	0.23
112	grass_mix	2095	2510	-17	0.19
112	legume_mix	2088	2510	-17	0.17
112	pea	2117	2510	-16	0.29
112	root_mix	2093	2510	-17	0.17
168	All	1908	2570	-26	0.07
168	Brassica_mix	2081	2570	-19	0.12

Table S2 continued

N_rate Kg/ha	**Cover_crop**	**Mean_CC Kg/ha**	**Mean_Fallow Kg/ha**	**% change from fallow**	**p_value**
168	grass_mix	1995	2570	-22	0.07
168	legume_mix	2097	2570	-18	0.14
168	pea	2192	2570	-15	0.36
168	root_mix	1969	2570	-23	0.06

Protein

Table S3. Percent change in grain protein content under cover crop treatments relative to fallow across years. Values are expressed as percent change compared to fallow within each year, and p-values indicate whether protein content under each cover crop differs significantly from fallow at $\alpha = 0.05$.

Year	Cover_crop	Mean_CC Kg/ha	Mean_Fallow Kg/ha	% change from fallow	p_value
2020	All	11.8	12.4	-5	0.09
2020	Brassica_mix	11.6	12.4	-7	<0.05
2020	grass_mix	11.7	12.4	-6	<0.05
2020	legume_mix	11.9	12.4	-5	0.12
2020	pea	12.3	12.4	-1	0.69
2020	root_mix	11.8	12.4	-5	0.08
2021	All	18.5	17.2	7	0.12

Table S3 continued

Year	Cover_crop	Mean_CC Kg/ha	Mean_Fallow Kg/ha	% change from fallow	p_value
2021	Brassica_mix	17.9	17.2	4	0.25
2021	grass_mix	17.9	17.2	4	0.3
2021	legume_mix	18.6	17.2	8	<0.05
2021	pea	19.1	17.2	11	<0.05
2021	root_mix	18.1	17.2	5	0.19

2022	All	14.6	14.4	1	0.77
2022	Brassica_mix	14.4	14.4	0	0.99
2022	grass_mix	14.4	14.4	0	0.97
2022	legume_mix	14.9	14.4	3	0.37
2022	pea	16	14.4	11	<0.05
2022	root_mix	14.6	14.4	1	0.77
2023	All	13.6	13.5	1	0.89
2023	Brassica_mix	13.6	13.5	1	0.89
2023	grass_mix	13.5	13.5	0	0.98
2023	legume_mix	13.6	13.5	1	0.86
2023	pea	14.4	13.5	7	0.23
2023	root_mix	13.5	13.5	0	0.99
2024	All	13.6	13.5	0	0.94
2024	Brassica_mix	13.6	13.5	1	0.9
2024	grass_mix	13.5	13.5	0	0.97
2024	legume_mix	13.6	13.5	1	0.82
2024	pea	14.4	13.5	7	0.23
2024	root_mix	13.5	13.5	0	0.97

Table S4. Percent change in grain protein content under cover crop treatments relative to fallow across N rates. Values are expressed as percent change compared to fallow within each nitrogen level, and p-values indicate whether protein content under each cover crop differs significantly from fallow at $\alpha = 0.05$.

N_rate	Cover_crop	Mean_CC	Mean_Fallow	Change (%)	p_value

0	All	12.3	12.1	2	0.71
0	Brassica_mix	12	12.1	0	0.97
0	grass_mix	12.3	12.1	2	0.65
0	legume_mix	12.4	12.1	2	0.58
0	pea	12.9	12.1	7	0.18
0	root_mix	12.2	12.1	1	0.81
56	All	13.4	13.5	0	0.96
56	Brassica_mix	13.5	13.5	0	0.99
56	grass_mix	13.2	13.5	-2	0.61
56	legume_mix	13.7	13.5	2	0.69
56	pea	14.8	13.5	10	0.07
56	root_mix	13.4	13.5	0	0.96
112	All	15.3	15.4	-1	0.88
112	Brassica_mix	15	15.4	-3	0.49
112	grass_mix	15.1	15.4	-2	0.57
112	legume_mix	15.4	15.4	0	0.92
112	pea	16.1	15.4	5	0.27
112	root_mix	15.1	15.4	-2	0.56
168	All	16.6	15.9	4	0.33
168	Brassica_mix	16.4	15.9	3	0.43

Table S4. continued

N_rate	**Cover_crop**	**Mean_CC**	**Mean_Fallow**	**Change (%)**	**p_value**
168	grass_mix	16.3	15.9	2	0.57
168	legume_mix	16.5	15.9	4	0.29
168	pea	17	15.9	7	0.11

168	root_mix	16.5	15.9	4	0.33

Table S5. Pairwise differences in wheat protein between individual cover crop treatments and fallow, based on mixed-model contrasts,and averaging across all replicates, years, and N fertilizer rates.

Variable	**Difference %**	**T.Ratio**	**P_Value**
All - Fallow	0.19	1.5	0.49
Brassica_Mix - Fallow	0.01	0.1	0.999
Grass_Mix - Fallow	-0.02	-0.2	0.999
Legume_Mix - Fallow	0.3	2.6	<0.05
Pea - Fallow	1.01	7.7	<0.05
Root_Mix - Fallow	0.09	0.8	0.89

Differences represent absolute percentage-point differences in grain protein concentration (%) between each CC treatment and fallow, derived from mixed-model pairwise contrasts, averaged across all replicates, years, and N rates. For example, the Pea − Fallow difference of 1.01 was calculated as: mean grain protein under pea (15.1%) minus mean grain protein under fallow (14.1%) = 1.01 percentage points

Agronomic Nitrogen Use Efficiency

Table S6. Percent change in agronomic nitrogen use efficiency (ANUE) under cover crop treatments relative to fallow across years. Percent change values indicate the relative difference in ANUE compared to fallow within each year, and p-values denote statistical significance at $\alpha = 0.05$.

Year	Cover_crop	Mean_CC	Mean_Fallow	Change (%)	p_value
2020	All	13	37	-66	<0.05
2020	Brassica_mix	24	37	-34	<0.05
2020	grass_mix	22	37	-41	<0.05
2020	legume_mix	16	37	-58	<0.05
2020	pea	33	37	-11	0.51
2020	root_mix	26	37	-32	<0.05
2021	All	5	10	-50	0.26
2021	Brassica_mix	5	10	-54	<0.05

Table S6. continued

Year	Cover_crop	Mean_CC	Mean_Fallow	Change (%)	p_value
2021	grass_mix	6	10	-40	0.18
2021	legume_mix	7	10	-31	0.28
2021	pea	4	10	-58	0.19
2021	root_mix	8	10	-17	0.55
2022	All	5	13	-63	<0.05
2022	Brassica_mix	8	13	-39	<0.05
2022	grass_mix	7	13	-43	0.06
2022	legume_mix	4	13	-66	<0.05
2022	pea	3	13	-74	<0.05
2022	root_mix	5	13	-62	<0.05
2023	All	32	50	-36	<0.05
2023	Brassica_mix	38	50	-25	0.07
2023	grass_mix	34	50	-32	<0.05
2023	legume_mix	32	50	-36	<0.05
2023	pea	39	50	-22	0.21
2023	root_mix	39	50	-22	0.1
2024	All	16	19	-18	0.29
2024	Brassica_mix	19	19	0	0.99
2024	grass_mix	16	19	-19	0.3
2024	legume_mix	16	19	-19	0.28
2024	pea	24	19	23	0.28
2024	root_mix	18	19	-7	0.68

Table S7. Percent change in agronomic nitrogen use efficiency (ANUE) under cover crop treatments relative to fallow across N rates.

Percent change values indicate the relative difference in ANUE compared to fallow within each nitrogen level, and p-values denote statistical significance at $\alpha = 0.05$.

N_rate	Cover_crop	Mean_CC	Mean_Fallow	Change (%)	p_value
56	All	14	33	-58	<0.05
56	Brassica_mix	23	33	-30	0.13
56	grass_mix	17	33	-49	<0.05
56	legume_mix	17	33	-50	<0.05
56	pea	28	33	-16	0.51
56	root_mix	23	33	-30	0.13
112	All	17	23	-25	0.17
112	Brassica_mix	19	23	-16	0.37
112	grass_mix	21	23	-7	0.74
112	legume_mix	15	23	-34	<0.05
112	pea	20	23	-14	0.55
112	root_mix	21	23	-10	0.59
168	All	11	22	-48	<0.05
168	Brassica_mix	14	22	-35	<0.05
168	grass_mix	13	22	-42	<0.05
168	legume_mix	13	22	-39	<0.05
168	pea	15	22	-33	0.12
168	root_mix	14	22	-38	<0.05

Table S8. Differences in agronomic nitrogen use efficiency (ANUE) between individual cover crop treatments and fallow, based on

mixed-model contrasts.

Variable	Diff	T.Ratio	P_Value
All - Fallow	-12	-6	<0.05
Brassica_Mix - Fallow	-7	-4	<0.05
Grass_Mix - Fallow	-9	-5	<0.05
Legume_Mix - Fallow	-11	-6	<0.05
Pea - Fallow	-5	-3	<0.05
Root_Mix - Fallow	-7	-4	<0.05

Aggregate Stability

Table S9. ANOVA contrasts comparing cover crop treatments with fallow for aggregate stability at 0–5 cm depth under 112 kg N ha^{-1}, showing mean differences (treatment − fallow, with significance at $p < 0.05$.

Comparison	Estimate	t_value	p_value
All - Fallow	0.04	0.59	0.94
Brassica Mix - Fallow	0.21	3.3	<0.05
Grass Mix - Fallow	0.17	2.7	<0.05
Legume Mix - Fallow	0.04	0.66	0.92
Pea - Fallow	0.14	2.2	<0.05
Root Mix - Fallow	0.18	2.89	<0.05

Field Saturated Hydraulic Conductivity

Table S10. One-way ANOVA comparing individual cover crop treatments with fallow for field saturated hydraulic conductivity (Kfs; $\alpha = 0.05$).

Comparison	Df	F_Value	P_Value
All vs Fallow	1	0.12	0.74
Brassica Mix vs Fallow	1	1.13	0.33
Grass Mix vs Fallow	1	2.1	0.2
Legume Mix vs Fallow	1	2.61	0.16
Pea vs Fallow	1	0.4	0.55
Root Mix vs Fallow	1	0.68	0.44

Plant available water

Figure S1. Response ratios (RR; CC/Fallow) for Plant available water (PAW) across CC. Soil depths (0–5 cm and 5–10 cm) under 0 and 112 kg N ha^{-1}. Points represent mean response ratios with 95% confidence intervals; the vertical red dashed line indicates fallow

(response ratio = 1). Different letters within each depth × nitrogen panel indicate mean separation based on pairwise_comparison with fallow (α = 0.05).

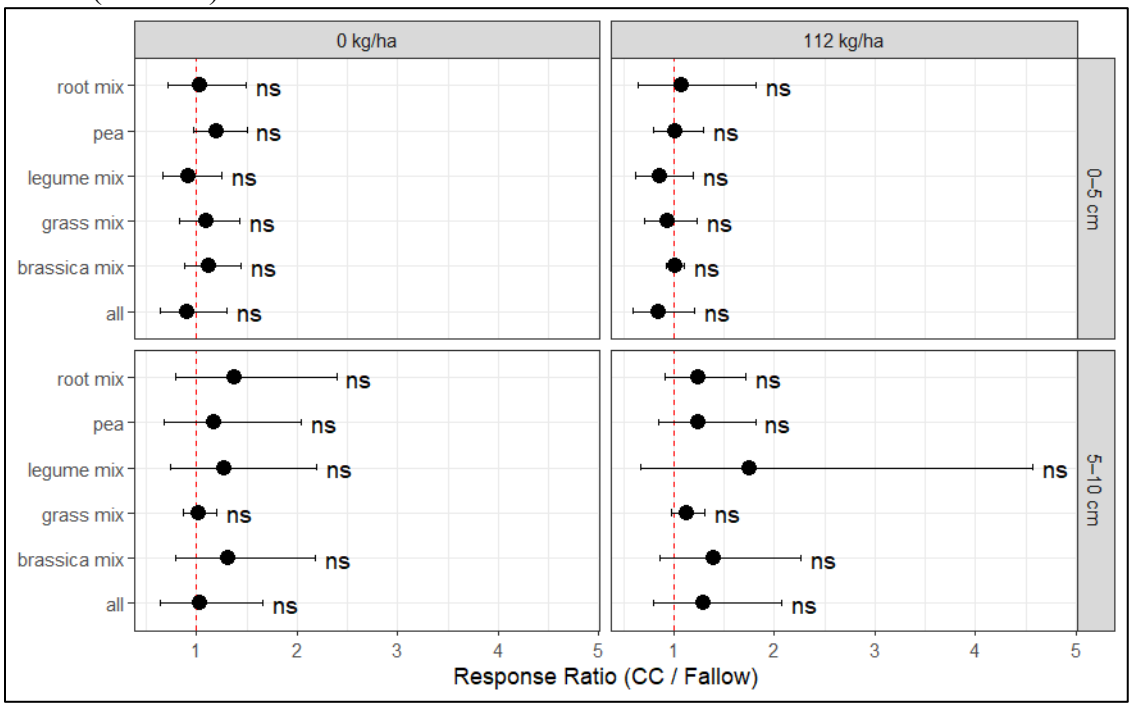

Table S11. Thousand kernel weight (TKW), target plant density, and seeding rates for cover crop species by functional group across experimental years (2018–2023). Mixture seeding rates were adjusted proportionally by the number of species.

Cover Crop Species Seeding Rates — all Years									
Functional Group	**Species**	**Variety**	**2018**	**2019**	**2020**	**2022**	**2023**	**Target Density (plants/ft²)**	**Seeding Rate (lbs/ac)†**
Legume (L)									
	Spring pea	Salamanca	208.3	208	221.2	219.6	264	8	202.6
	Cowpea	Iron & Clad	—	103	118.3	109	92	6.5	57.4
	Fababean	Boxer	249.7	259	167	214	483	4	185.4
	Chickpea	Royal	185.4	394	—	380	456	4	175
Grass (G)									
	Oat	Monida	—	33.3	28.4	29.9	29	25.5	70.9
	Millet	White Wonder	—	2.7	2.2	2.8	2.8	40	10.7
	Triticale	—	46	40	40	44.6	30	19	54.7
	Corn	—	190.3	190.3	283.2	284	268	0.5	12.9
Brassica (B)									
	Radish	Nitro	—	17.1	15	14.6	14.5	6	8.3
	Mustard	White Gold	—	2.8	2.4	2.5	6.1	9	5.3
	Turnip	Purple Top	—	2.1	2.1	2.5	2.4	6	1.4

Table S11 continued

Functional Group	Species	Variety	2018	2019	2020	2022	2023	Target Density	Seeding Rate
	Canola	Trpphy	—	4.3	4.1	4.2	4.2	9	3.6
Taproot (R)									
	Safflower	Nutrasaf	—	38.1	33.1	31	29	8	22.3
	Flax	Glas	5.6	5.6	—	4.5	4.4	40	16.9
	Buckwheat	Mancan	—	—	34.8	27.2	35	15	50.4
	Sunflower	Black Oil	—	—	52	62.9	61	0.7	4.1