Agronomics and ecology of wheat-based cropping systems: unveiling dynamics for sustainable agriculture

by

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B.S., University of São Paulo, 2018
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

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Abstract

Wheat (*Triticum aestivum* L.) area has dramatically reduced in major wheat-producing nations such as the United States, Canada, China, and Turkey. This reduction is primarily attributed to the expansion of more attractive crops such as maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.). Decreasing wheat area poses risks in regions where wheat is a staple, given its multitude of benefits and ecosystem services to cropping systems. Furthermore, introducing wheat into rotations in areas where it hasn't historically been a major crop could yield substantial advantages for overall sustainability and productivity. Our overarching goal was to evaluate the benefits and challenges of maintaining wheat in more intensified cropping systems. Our specific goals were to: (i) outline benefits of adding wheat to simple crop rotations (i.e., one to three rotational crops) by reviewing ca. 300 peer-reviewed studies worldwide; (ii) examine the long-term (44-yr) application of conservation agriculture principles (i.e., minimal soil disturbance, crop rotation, and permanent soil cover) on grain yield, yield stability, and adaptability of winter wheat, soybean, and grain sorghum (*Sorghum bicolor* (L.) *Moench*); and (iii) evaluate the impact of intensification of cropping systems and nitrogen (N) management on the wheat phase of the system. In our review to address the first objective, we highlighted the wheat's versatility for tactical in-season crop management [e.g., flexible sowing dates, crop type (winter vs. spring), and N fertility] and strategic cropping system management (e.g., grazing and double-cropping) and provided evidence supporting the positive impact of wheat on the grain yield and yield stability of other rotational crops. The introduction of wheat to simple crop rotations can (i) interrupt pest population cycles by serving as a break crop; (ii) decrease N application requirements, thus reducing N losses, greenhouse gas emissions, soil acidification, and production costs; (iii) improve soil health and carbon sequestration; (iv) increase resource use-

efficiency of the cropping system; (v) foment fauna populations, and (vi) decrease variability in economic returns. In response to our second objective, we summarized results from a long-term (1973 – 2018) field experiment near Ashland Bottoms, KS that evaluated three tillage systems (no-till, reduced till, and conventional till) and five 2-yr crop rotations (continuous winter wheat, soybean, and grain sorghum; and soybean-grain sorghum and soybean-winter wheat). Crop rotation consistently out-yielded continuous cropping and the advantage was enhanced when integrated with no-till. Wheat was adaptable to low- and high-yielding environments with similar grain yield and yield stability among treatments, except for no-till continuous wheat, which had the lowest yield stability and grain yield (2.5 *vs.* 3.5 Mg ha^{-1}). Soybean grown after wheat was more adaptable to low-yielding environments and grown after sorghum to high-yielding environments. To answer our third objective, a field experiment near Ashland Bottoms, KS, evaluated sixteen combinations of three N-management strategies (Green N, Standard, and Progressive) and nine crop sequences. Green N did not receive external N supply and it was implemented in a rotation constructed to supply N through biological fixation from previous legume crop. Standard consisted of a baseline N-management, while Progressive was an intensified N-management where all “4R” (right rate, time, source, and placement) were simultaneously improved. Crop sequences were either Grain Only or Dual-Purpose systems with different levels of intensification. Both standard and progressive N management practices had similar results within crop sequences, but Green N decreased dual-purpose winter wheat grain yield and shoot biomass. Cropping systems that allowed winter wheat to be sown at the optimum date had the greatest yields. Later sowing dates were most likely to reduce plant available water at sowing, mainly when following a summer crop, and could delay wheat’s development resulting in higher temperatures during the critical period for yield determination (i.e., the days surrounding anthesis) and shorter grain filling duration. Results from this research highlight that wheat offers unique opportunities to increase diversification and foster more sustainable and resilient agroecosystems.

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cropping system; (v) foment fauna population, and (vi) decrease variability in economic returns. In response to our second objective, a long-term (1973 – 2018) field experiment near Ashland Bottoms, KS evaluated three tillage systems (no-till, reduced till, and conventional till) and five 2-yr cropping systems (continuous winter wheat, soybean, and grain sorghum; and soybean-grain sorghum and soybean-winter wheat rotations). Crop rotation consistently out-yielded continuous cropping and the advantage was enhanced when integrated with no-till. Wheat was adaptable to low- and high-yielding environments with similar grain yield and yield stability among treatments, except for no-till continuous wheat, which had the lowest yield stability and grain yield (2.5 *vs.* 3.5 Mg ha^{-1}). Soybean grown after wheat was more adaptable to low-yielding environments and grown after sorghum to high-yielding environments. To answer our third objective, a field experiment near Ashland Bottoms, KS, evaluated three levels of N-management (Standard, Intensive, and Green N) combined with nine crop sequences with different levels of crop intensification (continuous winter wheat, less intensive, semi-intensive, intensive, more intensive, dual-purpose [DP] summer forage, DP semi intensive, DP intensive, and DP Green N) from 2019 – 2023. Both standard and progressive N management practices had similar results within crop sequences, and Green N decreased dual-purpose winter wheat grain yield and shoot biomass. Cropping systems that allowed winter wheat to be sown at the optimum date had the greatest yields. Later sowing dates were most likely to reduce plant available water at sowing, and could delay wheat's development resulting in higher temperatures occurring during the critical period for yield determination (i.e., the days surrounding anthesis) and shortening grain filling duration. This research highlights that wheat offers unique opportunities to increase diversification and foster more sustainable and resilient agroecosystems.

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Dedication

To Luiz, Nilza, Carlos, and Alek who has been my biggest supporters and motivation. I could not have done this without you.

"The most scientifically certain things are the most existentially irrelevant ones. Of the most important things for us, we are usually not sure at all."

Unknown

Preface

This dissertation delves into the intricate dynamics of global agriculture, specifically focusing on wheat-based cropping systems. Comprising three fundamental chapters, the research collectively elucidates the interplay between agronomics and ecology, emphasizing their interconnected implications for food security and sustainability. Chapter 1 sets the stage by delving into the global context of wheat production, examining the stability and shifts in wheat cultivation. It navigates through the complexities of reduced wheat acreage, exploring the potential consequences for regions reliant on wheat as a staple crop. Additionally, it addresses emerging environmental concerns, highlighting the risks associated with monocropping trends and their impact on system stability and resilience.

Chapter 2 expands the discourse into the realm of conservation agriculture, a system heralded for its potential to address environmental challenges while meeting the demands of a growing population. The chapter scrutinizes individual practices within conservation agriculture, seeking to quantify the conditions under which these practices contribute to enhanced crop yield and yield stability. This exploration is crucial for aligning conservation agriculture with the goal of sustainable and resilient cropping systems.

Chapter 3 takes a focused lens to Kansas, a significant wheat-producing state in the U.S. The state's cropping systems, predominantly centered on winter wheat, provide a backdrop for examining the intricate relationship between sowing dates and winter wheat yield. The chapter delves into the variations in sowing dates influenced by cropping systems, especially in the context of double-cropping with summer crops. It also addresses the pressing issue of the approximate 50% winter wheat yield gap in Kansas, attributing it to poor nitrogen management and the influence of cropping systems on sowing dates.

Together, these chapters weave a narrative that transcends individual facets, creating a comprehensive tapestry that explores the intricate connections between wheat-based cropping systems, agronomics, and ecology. As we navigate through these chapters, the dissertation aims to contribute insights that not only enrich our understanding of these complex systems but also offer pathways towards sustainable and resilient agricultural practices on a global scale.

Chapter 1 - Beyond grain: agronomic, ecological, and economic benefits of diversifying crop rotations with wheat

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Abstract

Global wheat production has remained stable in the last 20 yr, benefiting from increased grain yields despite the decline in harvested wheat area. Here, we conducted a comprehensive review of ca. 300 peer-reviewed studies worldwide to outline benefits of adding wheat to simple crop rotations (i.e., one to three rotational crops). We highlight wheat's versatility for tactical in-season crop management [e.g., flexible sowing dates, crop type (winter vs. spring), and nitrogen fertility] and strategic cropping system management (e.g., grazing and double-cropping) and provide evidence supporting the positive impact of wheat on grain yield and yield stability of other rotational crops. The inclusion of wheat in simple cropping systems enhances agroecosystem diversity and improves resilience to biotic and abiotic stresses. The high carbon-to-nitrogen ratio (C:N) residue of wheat offers benefits and drawbacks for soil quality attributes, weed control, and climate change mitigation potential. The introduction of wheat to simple crop rotations can (i) interrupt pest population cycles by serving as a break crop; (ii) decrease N application requirements, thus reducing N losses, greenhouse gas emissions, soil acidification, and production costs; (iii) improve soil health and carbon sequestration; (iv) increase resource use-efficiency of the cropping system; (v) foment fauna populations, and (vi) decrease variability in economic returns. Wheat offers unique opportunities to increase diversification and foster

more sustainable and resilient agroecosystems that will feed a growing global population while acting as a net carbon sink, helping to mitigate drivers of climate change.

Introduction

Wheat (*Triticum aestivum* L.) provides approximately 21% of the world's food calories and protein (FAO, 2021). Global wheat production has remained relatively stable over the past two decades due to increased grain yields and geographical shifts in production with increases in regions such as Russia, Brazil, and Argentina (FAO, 2021). Still, some of the largest wheat producing countries have experienced a decline in harvested wheat hectares in the last 20 years (e.g., China, United States, Canada, and Turkey; FAO, 2021), mostly due to expanding production of more profitable crops such as maize, *Zea mays* L., and soybean, *Glycine max* (L.) Merr. We argue that reduced wheat area can be detrimental to areas where wheat has been historically a major crop due to the many benefits and ecosystem services that it provides to cropping systems. Further, many cropping systems in regions where wheat has not been a major crop in the past could also benefit from the inclusion of wheat in their rotations. We do not argue for the adoption of monocrop wheat systems, as these may suffer from a number of drawbacks and can potentially benefit from break crops (Kirkegaard et al., 2008), but rather support the inclusion of wheat in cropping systems to enhance their resilience and minimize environmental impacts. Here, we first describe the role of wheat as a primary food crop, and then elucidate how other crops such as maize, soybean, grain sorghum, *Sorghum bicolor* (L.) Moench, cotton, *Gossypium hirsutum* L., and canola, *Brassica napus* L., respond to the addition of wheat in crop rotations. We also review the various benefits of wheat to agroecosystem sustainability in various environmental, agronomic, and economic contexts.

The role of wheat in the global food supply chain

Feeding a growing global population with increased per capita purchasing power poses a substantial threat for sustainable agriculture owing to the escalating demand for nutrient-dense food (Godfray et al., 2010). Increasing food production without expanding agricultural land and displacing native vegetation will require increasing crop productivity in a sustainable manner (Cassman & Grassini, 2020) without exploiting natural resources at a pace that surpasses the Earth's ability to replenish them (Godfray et al., 2010). Recent events like the COVID-19 pandemic and social conflicts such as the Ukraine and Russia war have revealed the vulnerability of global food supply chains and the necessity for increased local diversification of crop production to improve global food security (Junior et al., 2022). Historically, increases in food production involved ‘extensification’, i.e., bringing new land into cultivation; however, competing human activities make this an increasingly unviable and expensive option, particularly as protection of biodiversity and the public goods and services offered by natural ecosystems (e.g., carbon (C) storage in rainforests) are given greater priority by national governments (Pretty, 2008). Whereas global grain production has more than doubled over the last 50 years, the area of arable land under cultivation has only increased by about 9% (Pretty, 2008). Furthermore, highly productive agricultural lands are often lost to urbanization and other human uses (Andrade et al., 2022), while much land remaining under cultivation often loses productivity due to unsustainable management practices that lead to desertification, salinization, and soil erosion (Nellemann & Corcoran, 2009). Consequently, increased food production will have to be generated per unit of land, i.e., agricultural ‘intensification’.

About 30% of global wheat production is centered in temperate regions of North America and Europe (USDA, 2022), rendering the world's wheat supply vulnerable to environmental stresses in those regions (Cassman & Grassini, 2020). Although global wheat yield has increased by 13% in the last decade (FAO, 2021), the harvested area has remained relatively stable, and has decreased in some historically important wheat growing regions. For example, while the wheat area has remained stable or increased in Asia, Africa, and South America, it has decreased in North America, Europe, and Oceania (FAO, 2021).

The decrease in wheat area can be attributed to various factors, including the adoption of new technologies that have made other crops more appealing to farmers (Cooper et al., 2014), fluctuating wheat prices (Deen et al., 2016; Mulik, 2015), and changes in local land use policies (Anderson et al., 2001). For instance, government commodity program payments (Broussard et al., 2012), crop insurance (Bowman and Zilberman, 2013; MacDonald et al., 2013), biofuel policies (Aguilar et al., 2015; Fausti, 2015), and the increasing financialization of commodity markets (Clapp, 2012) have contributed to lower crop diversification in the U.S. Corn Belt compared to other regions (Aguilar et al., 2015; Roesch-McNally et al., 2018).

Integrating greater crop diversity faces challenges due to the current trend towards specialization rather than diversification, resulting in landscape-scale homogeneity (Cash et al., 2006). Roesch-McNally et al. (2018) suggested that financial incentives encouraging alternative cropping systems, such as biomass or small grains production, could lead to more diverse rotations on farms. The authors suggest strategies to overcome these challenges and promote diverse rotations in the U.S. Corn Belt, including increasing financial incentives through programs like the Conservation Stewardship Program and investing in alternative markets for small grains and biofuels.

When international wheat prices become more volatile, farmers tend to allocate less land to wheat or reduce investments in yield-improving techniques, ultimately leading to a decrease in wheat production (Haile et al., 2016). For example, the Great Plains and the Midwest regions of the US, which historically have been major wheat-producing regions, have shifted substantial wheat area to maize and/or soybean (Anderson et al., 2001; Mulik, 2017), resulting in a simplified 2 yr maize-soybean rotation, as highlighted in several recent surveys of management practices (e.g., Grassini et al., 2011, 2015). This shift has raised concerns about environmental sustainability due to loss of biodiversity, which could adversely affect crop yields and global food security compared to rotations that include wheat (Gaudin et al., 2015b). Risks include reduced system stability (i.e., ability to cope with biotic and abiotic stresses to maintain productivity) and resilience (i.e., the ability of a system to assimilate disturbance and retain essential functions during the period of change) (Holling, 1973; Walker et al., 2004), both of which are key to sustaining agricultural productivity in the face of environmental stresses like climate change and the evolution of pesticide-resistant pests (Lin, 2011). The review of Liu et al. (2022) highlighted the evidence suggesting crop diversification enhances cropping system resilience. Whereas many US farmers acknowledge the advantages of diversifying a 2-yr maize-soybean rotation, the challenge of identifying alternate crops with similar or better financial returns currently limits the inclusion of other crops in rotation (Roesch-McNally et al., 2018). Wheat is one of the main crops historically grown globally and is widely adaptable to many environments (Acevedo et al., 2002). As a C3 plant, wheat flourishes across a spectrum of environments, ranging from temperate to warm, and from humid to arid conditions, particularly exceling in cooler environments.

Wheat within cropping systems

This section describes the versatility of wheat within cropping systems and summarizes the findings of long-term experiments that analyze the benefits and limitations of wheat in crop rotations. Numerous studies have demonstrated that wheat can significantly improve yield and yield stability in a subsequent crop, specifically maize, soybean, cotton, and canola in a variety of tillage systems and nitrogen (N) management strategies, although a few studies found neutral effects, and fewer studies found negative effects.

Wheat as a versatile crop

The most critical period for yield determination in wheat is from onset of stem elongation until ~10 d post anthesis, when grain number is defined (Fischer, 1985). Thus, assuming successful stand establishment, early wheat vegetative growth is not as important determining grain yield as the growth, duration, and resources partitioning during the critical period (Slafer et al., 2023). This provides flexibility in management and crop utilization alternatives (Fig. 1.1).

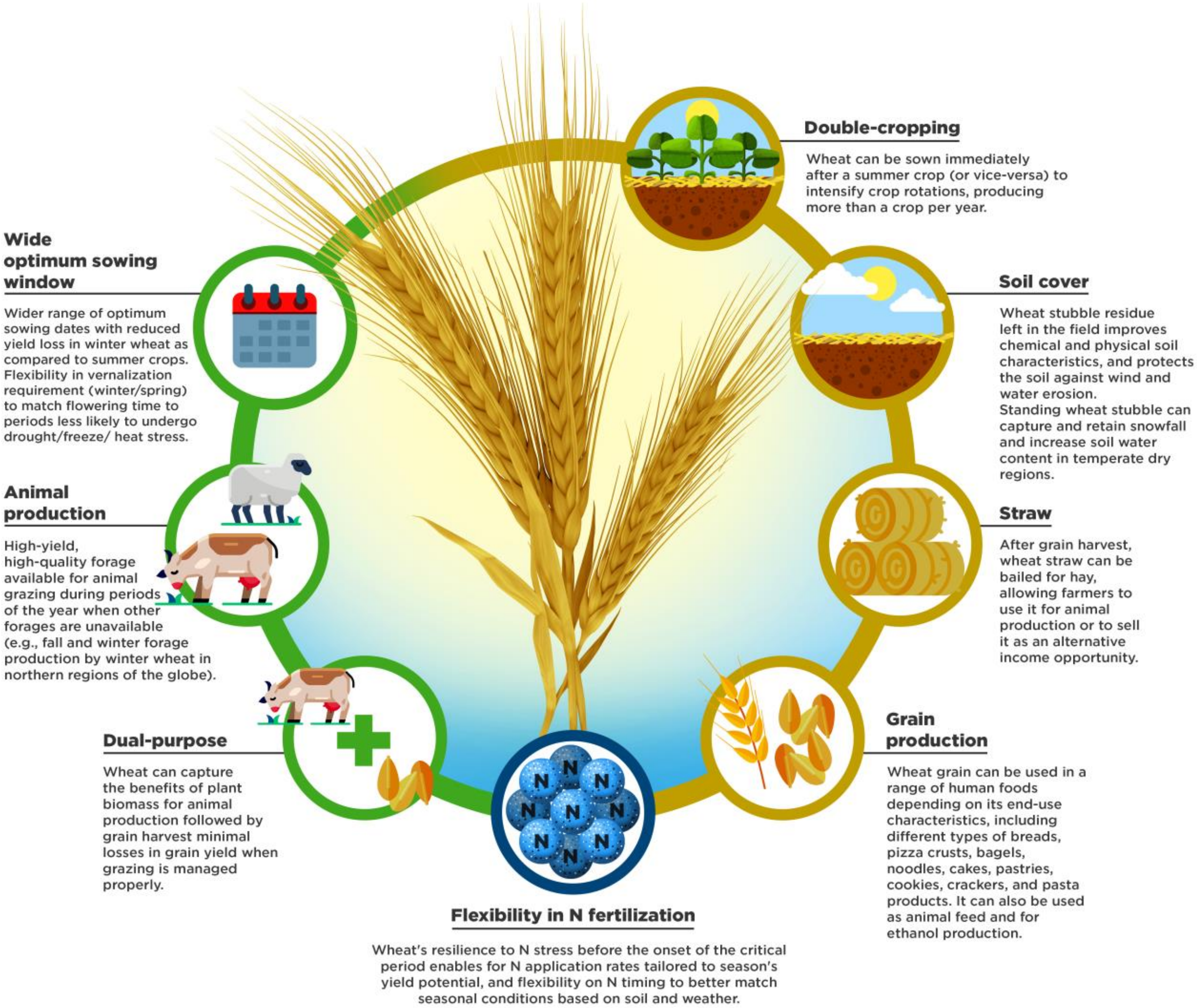

Fig. 1.1 Schematic representation of the uses and opportunities of wheat in a farming system.

Tactical in-season management

Wheat yields are relatively insensitive to suboptimal conditions during vegetative growth, enabling famers to select management alternatives those that best match environmental conditions and crop development (Slafer et al., 2023). For example, low sensitivity to vegetative growth provides improved flexibility in sowing dates, particularly for winter wheat, compared to spring-planted crops (e.g., spring wheat, maize, soybean) with a more defined growth window. Warm regions of the US Great Plains have particularly wide sowing windows for winter wheat –

as much as a 50-66 d range – where yield loss potential is less than 8-13 kg ha^{-1} d^{-1} (Jaenisch et al., 2021; Munaro et al., 2020). Whereas the optimum sowing window for winter wheat is narrower in colder, northerly regions (Jaenisch et al., 2021; Munaro et al., 2020), as well as many Mediterranean environments where sowing into stored soil moisture is limited to a 2-to 3-week time window (Cann et al., 2020; Donaldson, 1996), it is still wider than that of spring-planted summer crops, which tend to show a strong linear decrease in yield potential with delays in sowing, suggesting a narrower optimal window for attaining high yields (e.g., Edreira et al., 2017; Grassini et al., 2015). Sowing under appropriate conditions improves the probability of good stand establishment and high yield potential. With a wider optimum sowing window, growers have more flexibility selecting sowing date with appropriate conditions for crop emergence (e.g, soil moisture and temperature), which often vary yearly and along geographic gradients (Lollato et al., 2021).

In some regions, the cultivation of either spring or winter wheat genotypes offer additional flexibility (e.g., Cann et al., 2020; Entz & Fowler, 1991; Koppel et al., 2020; Krato & Petersen, 2012; Stoskopf et al., 1974), and provides opportunities to capitalize on optimum sowing conditions for these crops (although the yield of spring wheat is usually lower than that of winter wheat due to harsher environmental conditions during the critical period; Couëdel et al., 2021; Slafer et al., 2023). This flexibility in sowing time and crop type allows growers to explore genotypes with different vernalization requirements to maximize the chances of flowering during periods with minimal risk of drought, heat stress, and freeze damage (Flohr et al., 2018; Hunt et al., 2019).

The low impact of early growth stages on wheat grain yield also provides flexibility for timing N fertilization. Ravier et al. (2017) suggested that periods of N deficiency prior to the onset of stem elongation not only failed to decrease yield and grain protein content, but improved N use efficiency in some cases. These findings have been replicated elsewhere (Souza et al., 2022) and have contributed to the development and widespread adoption of remote sensing technologies for N rate determination in winter wheat. Remote sensing technologies for N management typically use canopy reflectance during the vegetative stages to estimate the yield potential of a field showing symptoms of N deficiency (Fig. 1.2A) relative to a reference “N-rich strip” (Mullen et al., 2003; Raun et al., 2001; Solie et al., 2002).

In support of the above rationale, we re-evaluated the data of Souza et al. (2022), where a fall-applied N treatment was compared to a zero N control, and subsequent treatments were established when N deficiency symptoms became detectable in the control via crop reflectance. Treatments consisted of the same N rate as the fall-applied N, but applications occurred at different times (i.e., 0, 7, 14, 21, 28, 35, 42, 49, 56, and 63 accumulated thermal units since N deficiency was first observed in the control). The last N application occurred 60 to 117 days after N deficiency symptoms were first observed. The experiment was conducted in 12 Oklahoma (US) environments in which the yield of the unfertilized control (Y_0) ranged from 1.3 to 3.5 Mg ha^{-1}. Yields (y) were expressed relative to yields in the fall-applied N treatment (Y_N) and were calculated as $y = 100 (Y_N-Y_0)/Y_0$ and which ranged from 13 to 172% (Fig. 1.2B). We re-analyzed these data by plotting differences in yield between N treatments applied after the onset of N deficiency (Y_t) and those in the fall-applied N treatment at each site [calculated as $y = 100 (Y_t-Y_N)/Y_N$] versus the number of days between N fertilization and the beginning of the critical period (Fig. 1.2C). The initiation of the critical period was modelled in each site-year using local weather and the wheat development model developed by Carlson and Edwards (2015). Here, negative *x* values indicate N applications that occurred during vegetative stages, whereas positive *x* values indicate N applications after the onset of the critical period; note that in both cases, the N was applied to wheat plants that were already N-deficient. The data follow a plateau-linear model, suggesting that N application to N-deficient wheat during the 107-d vegetative period prior to the onset of the critical period, resulted in yields that were 16% greater than yields obtained in the fall-applied N. The breakpoint of the model occurred at the onset of the critical period (estimate: 6 days; confidence interval [CI]: -6 to 18 days); applying N later than the onset of the critical period reduced yield differences from that obtained with fall-applied N at a rate of -0.7% d^{-1} (CI: -0.5 to -1.0% d^{-1}) (Fig. 1.2C). This demonstrates the ability of wheat to tolerate early N stress without yield penalty, which allows for adjustments of N application timing and accommodation of environmental conditions to reduce N losses, improve N use efficiency, and thus increase return on N-fertilizer investment (Giordano et al., 2023; Hu et al., 2021; Lollato et al., 2021). It also creates opportunities to adjust N rates to soil- and season-specific conditions affecting yield potential (Raun et al., 2008).

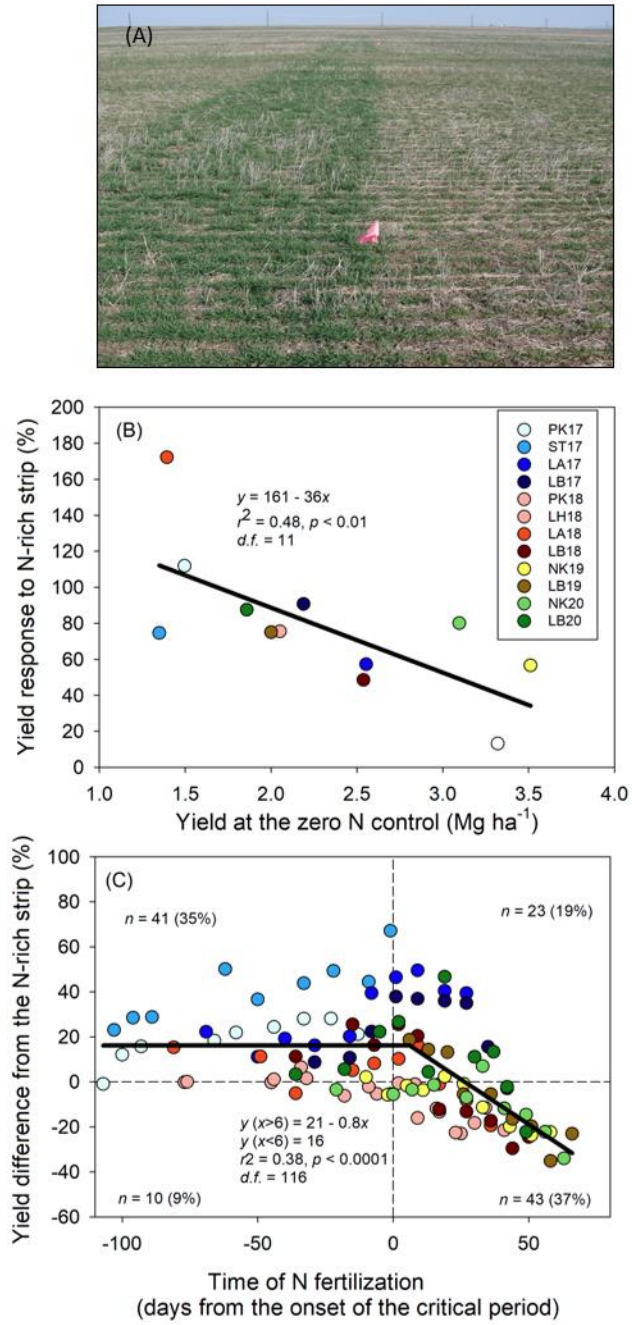

Fig. 1.2 Wheat can sustain nitrogen (N) deficiency during vegetative stages without yield penalty. (A) Use of N-rich strip technology to determine N rates for wheat using in-season canopy reflectance measurements (photo credit and approval for publication: Dr. Brian Arnall). This N-management tool makes recommendations for fields that are already N-deficient to aid crop recovery. (B-C) Re-analysis of Souza et al. (2022) data showing (B) yield response to fall-applied N versus the zero N control, as a function of zero N control yield, in 12 Oklahoma (US) environments; and (C) yield difference between N treatments applied at 0, 7, 14, 21, 28, 35, 42,

49, 56, and 63 thermal units after N-deficiency symptoms were first observed in the control, as a function of the time of N fertilization from the onset of the critical period in each environment. For experimental description and site-specific details, see Souza et al., 2022.

Strategic crop system management

The low sensitivity of grain yield to stresses during wheat vegetative growth allows for its use as a high-quality forage and as a dual-purpose crop (grazing plus grain), as reviewed by Harrison et al. (2011a). Dual-purpose pastures of wheat are common worldwide (Edwards et al¸ 2011; Hu et al., 2019; Sprague et al., 2021). According to Harrison et al. (2011a), wheat can be grazed for a short duration at medium to high intensities, as in Mediterranean climatic regions (e.g., Australia, Italy, West Asia, and Africa; Kelman & Dove 2009), or for a longer duration at a lower stocking rate, as in the US Great Plains (Holman et al., 2010; Khalil et al. 2002). Winter wheat can produce as much as 3.5 Mg of dry matter ha^{-1} and allow for as many as 120 to 150 days of grazing during fall and winter, a period when other forages are mostly unavailable (Holman et al., 2010). Spring wheat can also be pastured prior to harvesting for grain (Bartmeyer et al., 2011; Seymour et al., 2015), capturing the benefits of forage for animal production with negligible or minor tradeoffs in grain yield, providing that grazing is terminated prior to the onset of the critical period for yield determination (Slafer et al., 2023). This is high-quality forage, often containing 20 - 30% crude protein and less than 45% neutral detergent fiber, with high digestibility (Holman et al., 2010). This high-yield, high-quality forage allows for cattle, *Bos taurus* L., stocking rates of up to ~530 kg of animal ha^{-1} during fall and ~890 kg of animal ha^{-1} in early spring, with potential stocker gains of up to 1.1 kg d^{-1} (Lollato et al., 2017); and for as many as 30 d of grazing by Merino sheep, *Ovis aries*, at 1965 sheep ha^{-1} (Harrison et al., 2011b). This dual-purpose option allows for flexibility to completely graze out the crop as a pasture or remove cattle at the appropriate time to allow grain production (Edwards et al., 2011). This decision can be made on partial enterprise budgets for both cattle and grain (e.g., Lollato et al., 2018), permitting timely adaptation to market conditions. Finally, Harrison et al. (2011a) and Baumhardt et al. (2009) also suggested that grazing wheat in highly productive environments can reduce stubble loads and facilitate cultural operations in subsequent crops, although there is a slight risk of compaction in susceptible soils (Krenzer et al., 1989).

Another example of the versatility of wheat is its potential to be double-cropped with summer crops, either via delayed sowing of wheat after harvest of the summer crop (Staggenborg et al., 2003) or by delaying planting of the summer crop until after winter wheat harvest (Santos Hansel et al. 2019). This permits the intensification of cropping systems by allowing the cultivation of more than one cash crop per year in some summer-rainfall temperate regions where growing seasons are limited by cold winters (Purcell et al., 2003).

In subtropical regions with mild winters such as southern Brazil, the sowing a spring wheat crop in the fall can allow for a second cash crop within the same calendar year (Garbelini et al., 2022). For example, in the Cerrado region of Brazil, as many as 4.5-7.9 million hectares could be cultivated with wheat as a second crop (Pasinato et al., 2018). Agronomic recommendations on variety selection and sowing date (e.g., Galindo et al., 2017; Teixeira Filho et al., 2011, 2014) along with efforts to improve the crop’s tolerance to biotic (Cruppe et al., 2023; Weber et al., 2023) and abiotic factors (Pereira et al., 2019) such as high incidence of diseases and high temperatures at critical period (Pasinato et al., 2018).

Wheat impacts on the grain yield of other rotational crops

Several long-term studies around the world have shown that including wheat in a crop rotation can benefit the yield of other crops, both in humid and semi-arid regions. For example, a 10 yr study in Illinois, US, by Zacharias and Grube (1984) observed greater maize and soybean yields in a maize-soybean-wheat rotation than systems including only maize and/or soybean. In a long-term study (44 yr) in eastern Kansas, Simão et al. (2023) reported a 27% soybean yield increase in rotation with winter wheat compared to continuous soybean cultivation. In this case, soybean in rotation with winter wheat also had greater yield than soybean in rotation with grain sorghum. Similar results were reported by Marburger et al. (2015) in Wisconsin, US; both maize and soybean had a 5 to 8% yield increases when following wheat, and the authors concluded that including wheat in a maize-soybean rotation was one of the best management strategies to maximize yields in all three crops. Three later studies in Wisconsin, ranging in length from 7 to 10 yr, showed that the inclusion of winter wheat in a maize-soybean rotation increased maize and soybean yields by 8% and 22%, respectively, and maize yield was 15% greater (ca. +1.5 Mg ha^{-1}) in the maize-soybean-wheat rotation than in continuous maize (Kazula & Lauer, 2018). In Alabama, US, Edwards et al. (1988) found that soybean yields were 6% greater in a maize-soybean-wheat rotation compared to maize-soybean only. In Indiana, US, Martin et al. (1991) found greater soybean yields under a soybean-wheat-maize rotation than under soybean-maize, because the inclusion of wheat extended the period between two soybean crops, thereby reducing the frequency of soybean in the system, which was beneficial for yields. This trend was also observed in studies conducted in New York (Katsvairo & Cox, 2000b), South Dakota (Lehman et al., 2017), and Brazil (Garbelini et al., 2022). In eastern Canada, Gagnon et al. (2019) found that diminishing the frequency of soybean from every year (continuous soybean) to once every three years (maize-soybean-wheat) increased soybean yield by 0.20 Mg ha^{-1}. Although results were consistent for maize in the study, there was no significant yield benefit for moving from maize-soybeans to maize-soybean-wheat.

We retrieved data published in peer-reviewed manuscripts to compare the yield of maize and soybean when grown as monoculture, in maize-soybean rotation, and in maize-soybean-wheat rotation. Maize and soybean yields have been increased by adding wheat to the rotation compared to continuous plantings of these crops (Fig. 1.3). The mean difference between maize-soybean-wheat versus maize-soybean, or a monocrop, was positive and significantly different from zero in all instances except for maize under maize-soybean (inset box plots, Fig.s 1.3A and 1.3B). In all cases, the slope was not statistically different from one, suggesting that these yield benefits were consistent across yield environments and managements.

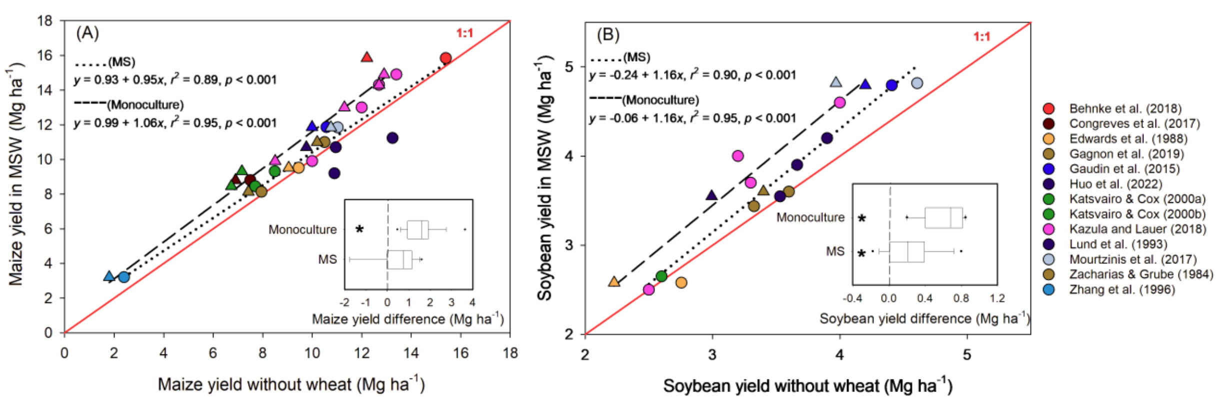

Fig. 1.3 Yield of (A) maize and (B) soybean when wheat (MSW = maize-soybean-wheat) is included in the rotation, compared to systems without wheat (MS = maize-soybean, dotted lines; and monoculture of soybean or corn, dashed lines) grown in the same experiments. Each symbol represents the overall effect of each treatment in a given experiment (different colors). Inset boxplot shows the mean benefit of adding wheat to a maize-soybean (MS) rotation and to maize or soybean monocultures. Asterisks indicate means significantly different from zero ($\alpha = 0.05$).

In a long-term (14 yr) study in Ontario, Canada, adding wheat to a maize-soybean rotation increased maize and soybean yields, averted yield losses due to zone-tillage, and increased N availability for maize via wheat shoot and root biomass mineralization, thus reducing N fertilizer requirements (Gaudin et al. 2015a). Furthermore, adding wheat to the system increased soybean yields by an average of 0.47 Mg ha^{-1} across tillage systems (conventional and zone-till) (Gaudin et al., 2015a). High N rates in maize negated the yield benefits of including wheat in the rotation; however, under low N rates, maize yields were similar to those under high rates if wheat was included in the rotation. Thus, the inclusion of wheat in maize-based systems reduced the amount of N amendment required to maximize maize yields while stabilizing the impact of tillage on crop yield.

Canola and chickpea, *Cicer arietinum* L., yields can also benefit from longer crop rotation intervals that include wheat. A long-term (30 yr) study in Canada showed that nodulation of chickpea and, consequently, grain yield, were both improved in rotation with spring wheat compared to chickpea planted continuously or rotated with mustard, *Brassica juncea* L. (Li J. et al., 2019). Harker et al. (2015) observed that the inclusion of spring wheat in the system increased canola yields in dryland regions of western Canada compared to continuous canola. In the study, for each additional crop between canola cycles, canola yield increased from 0.20 to 0.36 Mg ha^{-1}. Likewise, O'Donovan et al. (2014) observed that canola yields decreased 9% under continuous canola when compared to a canola–spring wheat rotation, and also showed promising results when canola followed faba bean, *Vicia faba* L. In both studies, wheat served to break canola disease cycles, which boosted canola yields.

Impact of wheat as an immediate previous crop

In North America, yields of summer crops are often greater following winter wheat than following another summer crop. For example, Zhang et al. (1996) found that maize yield was greater following one cycle of winter wheat and one cycle of a summer crop (either maize or soybean) than following two consecutive years of summer crops. A 6 yr study in New York (Singer & Cox, 1998b) compared maize-based crop rotations lengthening 2 yr under high and low chemical (e.g., herbicide) management regimes. Maize was planted following maize, soybeans, or wheat interseeded with red clover. Maize after wheat had greater yield (by ca. 2 Mg ha^{-1}) in both management regimes compared to maize after maize or maize after soybean. In Australia, Hulugalle and Scott (2008) concluded that cotton yields were greater following wheat or long fallow than following cotton, sorghum, or soybean, and that wheat is the preferred crop to rotate with cotton for ca. 70% of cotton producers in the New South Wales region. Canola yields were not only greater following wheat, but the advantage was evident across 115 observations under low-yielding potential conditions (Hegewald et al., 2018). Yield improvements following wheat resulted from small increases in multiple components of canola yield, such as plant population, number of seeds per pod, number of seeds per unit area, and root and shoot biomass.

The benefits of wheat for a subsequent crop are even more pronounced under water-limited conditions due to benefits for soil water storage (see Section 5.1). Grain sorghum yields were greater following winter wheat (+ ca. 1.8 Mg ha^{-1}) than following grain sorghum over a 20 yr study in semiarid western Kansas, US, with consistent results over the entire study period (Schlegel et al. 2017). Later, Schlegel et al. (2019b) reported greater yields of maize and grain sorghum following winter wheat compared to another summer crop, and that the most productive systems included grain sorghum after winter wheat. Similarly, a 24 yr study in semiarid eastern Colorado, US, found greater yields and better yield stability in winter wheat-based rotations that included one cycle of a summer crop and a long fallow period before planting of the subsequent crop, compared to those with two cycles of summer crop with short or no fallow periods (Nielsen & Vigil, 2018). Long fallow periods (10 to 11 months) in these regions are achieved by alternating winter wheat and summer crops and can promote soil water recharge in semiarid environments (see Section 5.1), which benefit the following crop.

Benefits of wheat for cropping system resilience and stability

Diversification of simple crop rotations (i.e., one or two crops per rotation) by adding wheat can enhance yield stability of the other crops in the system and increase grain yields. For example, Simão et al. (2023) concluded that soybean in rotation with winter wheat had greater yield and yield stability than continuous soybean over a 44 yr period. This benefit was irrespective of tillage system and seemed to be greater in low-yielding environments. In a 36 yr experiment in Ontario, Canada, Janovicek et al. (2021) observed a trend of maize and soybean yield increase associated with inclusion of wheat in rotations, with the advantage increasing over time (i.e., with more years in the rotation). In the same study, maize and soybean yields were greater and less variable when winter wheat was included in the rotation. In another (31 yr) experiment in Ontario, Gaudin et al. (2015b) used weather and yield data to test whether rotation diversity was associated with greater yield stability under abnormal weather conditions and found that diversification of a maize-soybean rotation with winter wheat increased soybean yields by 13% overall, and yield stability by 16% in dry years.

In semiarid regions, grain sorghum yields may improve over time when following winter wheat, whereas yields following grain sorghum remain stable (Schlegel et al., 2018). In a 16-yr study in Pennsylvania, including a small grain crop such as wheat or oats, *Avena sativa* L., and an interseeded legume (red clover, *Trifolium pretense* L./timothy, *Phleum pretense* L.) increased maize yields by 12% and improved yield stability over time compared to continuous maize (Grover et al. 2009). Furthermore, Congreves et al. (2017) observed that yield variability could be reduced by including winter wheat in a maize-soybean rotation in both conventional and no-tillage systems in Ontario, Canada.

Neutral or negative impacts of wheat on other crops

There are cases reported in literature in which including wheat in the cropping system did not benefit other crops. For example, an eight site-year study in Ohio, US, reported that including winter wheat in a maize-soybean rotation increased soybean yields in only two site-years, with no significant difference in the other six site-years, while maize yields were negatively affected in five site-years (Huo et al., 2022). This decrease in maize yield was attributed to slow emergence in wheat residue during cool, wet soil conditions and the persistence of inoculum of soilborne pathogens shared between wheat and maize. Consequently, it is common for producers in this region to remove and commercialize the wheat residue (see Sections 7.1 and 8). On the other hand, a study in a similar temperate environment found that maize yields improved by 1.1 Mg ha^{-1} by rotation with wheat and soybean under conventional tillage (Morrison et al., 2017). Inconsistent results are likely due to tillage effects, as the incorporation of wheat residues via conventional tillage negated the effects of cold, wet soils. Furthermore, the limitations associated with heavy wheat residues in cold, wet soils of temperate environments may not be specific to wheat but may arise from any crop that produces high residual biomass, including maize and sorghum.

Wesley et al. (1991) found that soybean had greater yield under monocropping (i.e., full-season soybean) than when it was double-cropped in rotation with winter wheat, although net returns for the rotation were greater than for monocrop. These results are not surprising, because double-cropped soybean has lower yield potential than full season soybean due to later sowing dates (Santos Hansel et al., 2019). The decline in yield with delayed sowing can range from 0.09% to 1.69% for each day of delay after the optimal sowing date, also varying with locality and maturity group (Edreira et al., 2017; Grassini et al., 2015; Salmerón et al., 2016). Late-sown soybean produces less biomass and fewer seeds due to lower radiation interception and experiences an increased risk of freeze events during grain fill (Egli & Hatfield, 2014; Seifert & Lobell, 2015). High-yielding wheat is usually harvested later than low-yielding fields due to a prolonged grain fill period (e.g., Lollato & Edwards, 2015). Thus, Santos Hansel et al. (2019) derived a relation suggesting that for each 100 kg ha^{-1} increase in wheat yield, yields of double-cropped soybean decrease ca. 13 kg ha^{-1}, which reflects the impact of delayed planting date on soybean yield. However, the direct impact on soybean yield is not the sole consideration, as there is extensive evidence demonstrating the economic benefits of diversifying soybean systems to reduce the financial risks associated with reliance on a single crop (see Section 8).

In other studies conducted in Wisconsin (Lund et al., 1993; Mourtzinis et al., 2017), New York (Singer & Cox, 1998a), and Illinois (Behnke et al., 2018), US, there was no maize and soybean yield effect when wheat was included a maize-soybean rotation possibly due to lack of water-limitation (see Section 5.1) and/or colder soil temperatures under the presence of heavy wheat residue (see Section 3.5). Morrison et al. (2017) did not find any yield benefit when soybean was rotated with maize and spring wheat compared to continuous soybean in a 15 yr study in Ontario, Canada, but under conventional tillage maize yielded better with rotation than when planted continuously.

These studies highlight the value of including wheat in diversified crop rotations to maximize crop yield, especially in maize-soybean rotations where it is particularly effective. The findings have important implications for farmers and agricultural policymakers and provide evidence-based recommendations for sustainable crop rotations.

Resource use efficiency

In water-limited rainfed farming systems, crop rotation strategies require careful consideration of precipitation use efficiency (PUE, i.e., the crop yield per unit of growing season precipitation) and precipitation allocation (PA, i.e., the precipitation received during the growing season divided by the total precipitation received during the entire crop rotation cycle), and water use efficiency (i.e., the amount of C assimilated as biomass or grain per unit of water uptake by the crop) (Huang et al., 2003; Pala et al., 2007; Peterson et al., 1993, 1996; Simão et al., 2023). A good way to improve the use efficiency of land, water, and radiation, and to cycle nutrients, is to rotate a cool-season crop with a warm-season crop such as maize, soybean, or grain sorghum which can enhance the utilization of both summer precipitation and snow accumulation (Nielsen et al., 2011; Patrignani et al., 2019). Crops compatible for rotation typically partition resource utilization across seasons and exhibit differences in water demand and rooting depth with adequate periods between harvest and planting to optimize soil water accumulation, N fixation, etc. A rotation in which a summer crop follows a winter crop can enhance land and water use efficiency (Nielsen et al., 2002; Hansen et al., 2012). In this section, we discuss how wheat presents an opportunity to enhance resource use efficiency.

Water and precipitation use efficiency

Given its relatively low water demand and high water use efficiency, wheat may improve the water use efficiency in cropping systems dominated by summer crops. Spring wheat depleted only 5.9 cm of soil water in North Dakota (Nash et al., 2017). In contrast, sunflower, *Helianthus annuus* L., removed 13.1 cm, safflower *Carthamus tinctorius* L., 11.9 cm, and soybean, 9.7 cm. Similar results were reported in eastern Montana (Black et al., 1981), in North Dakota (Merrill et al., 2007), and in eastern Colorado (Nielsen, 1997). Likewise, Gan et al. (2009) showed that alternating pulse crops with spring wheat in a semiarid environment improved water use efficiency in the cropping system due to the greater water use efficiency of wheat (7.0 kg ha^{-1} mm^{-1}) compared to oilseed crops such as canola, mustard, and flaxseed, *Linum usitatissimum* L., which averaged 3.6 kg ha^{-1} mm^{-1}, or pulse crops such as chickpea, dry pea, *Pisum sativum* L., and lentil, *Lens culinaris* Medik, which averaged 4.0 kg ha^{-1} mm^{-1}. The potential water use efficiency of wheat is 22 kg ha^{-1} mm^{-1} (Sadras and Angus, 2006; Lollato et al., 2017) which is greater than that of soybean (9 kg ha^{-1} mm^{-1}; Grassini et al., 2015) or sunflower (8 kg ha^{-1} mm^{-1}; Grassini et al., 2009), but lower than that of maize (28 kg ha^{-1} mm^{-1}; Grassini et al., 2011). These differences in mean and potential water use efficiency among crops under similar conditions are likely due to differences in grain composition as it relates to protein or lipid concentrations (Sinclair & de Wit, 1975). Additionally, wheat has a relatively high water use efficiency in comparison to summer crops, which may be partially explained by the timing of the critical period occurrence as it relates to atmospheric water demand. Couëdel et al. (2021) demonstrated that the critical periods for yield determination for major US winter wheat growing regions began in late April-early May, prior to the peak in annual temperatures and solar radiation. In contrast, the critical period for summer crops such as maize and soybean began in mid-late June and early July, corresponding with peak solar radiation, temperature, and atmospheric water demand. Although there is some variation around the globe, the timing of the critical period for wheat prior to peak atmospheric water demand can result in increased water use efficiency (Sadras & Angus, 2006).

In a temperate arid zone of northwest China, with 150 mm average annual rainfall and under irrigation, Yin et al. (2015) observed that wheat and maize relay-planting resulted in greater grain yields than monocropping. In the study, the combination of wheat straw mulch, relay crop, and reduced tillage increased soil water content on maize strips to a depth of 110 cm. The combination of reduced tillage and rotation of cotton with wheat improved water use efficiency of cotton under irrigation in a Vertisol soil in Australia (Tennakoon & Hulugalle, 2006). In Ontario, Canada, Renwick et al. (2021) observed that adding a wheat cycle to a maize-soybean no-tillage rotation improved the drought resistance of maize, ostensibly via effects on stomatal conductance. The presence of wheat residue can also improve water use efficiency, which for spring wheat sown under tall wheat residue (> 30 cm) was enhanced by 12% compared to residue cultivated before planting (Cutforth & McConkey, 1997; see Section 5.1).

Precipitation use efficiency and PA are two indices of rainfall use efficiency that can be used to evaluate dryland cropping systems under conditions of limited water availability (Patrignani et al., 2019; Simão et al., 2023). Wheat can increase PUE and PA in a cropping system partly due to the effects of its residue on soil moisture conservation (see Section 5.1) but also due to its presence during a time of the year when the land would otherwise be fallow, and precipitation mostly lost to evaporation and drainage. For example, for every 2.5 cm of precipitation stored as soil moisture during fallow after wheat, subsequent yields of grain sorghum may increase from ca. 385 kg ha^{-1} (Jones & Hauser, 1975) to 430 kg ha^{-1} (Baumhardt et al., 1985). Precipitation allocation and PUE in soybean systems were greater when winter wheat was double-cropped after soybean compared to a soybean-grain sorghum rotation, apparently due to the shorter fallow period in the former system (i.e., an effect on PA) and soybean yields were greater in rotation with winter wheat (i.e., effects on PUE) (Simão et al., 2023). Merrill et al. (2007) observed that spring wheat and chickpea in North Dakota, US, were the only crops that used precipitation efficiently without relying solely on the distribution of growing season precipitation for seed production, in contrast to maize, buckwheat, *Fagopyrum esculentum* Möench, and sunflower. The authors strongly encouraged the inclusion of spring wheat in cropping systems to improve their sustainability in the northern Great Plains of the US.

Dryland cropping systems of the southern High Plains typically rely on fallow periods between crops to accumulate precipitation as soil available water to stabilize and enhance the yields of subsequent crops. A 20 yr study in the semiarid High Plains of Kansas, US, revealed significantly higher grain sorghum water productivity and accumulation of soil water when the crop followed winter wheat compared to following another round of grain sorghum (Schlegel et al., 2017). When grain sorghum succeeded winter wheat, the available soil water at planting was ca. 34 mm greater at a depth of 180 cm, attributed to off-season accumulation. The experiment revealed a positive correlation between grain sorghum yields and the available soil water at planting. Grain yields reached ca. 4 Mg ha^{-1} or more with $\geq$ 250 mm of available soil water at a depth of 180 cm. There was a 40-45% chance of this outcome when grain sorghum followed winter wheat. In comparison, continuous grain sorghum had only a 20% chance of storing ≥ 250 mm of available soil water before planting. Subsequently, Schlegel et al. (2019a) observed that summer crops (grain sorghum, maize, and sunflower) had greater available soil water at planting and better crop water productivity, water use, and off-season soil water accumulation when they followed winter wheat versus another summer crop.

Nutrient use efficiency

Crop rotations can affect nutrient use efficiency directly by influencing nutrient utilization patterns and indirectly via effects on nutrient pools and sources (Pierce and Rice, 1988). For example, crop rotations can sometimes provide most of the nutrients required for a subsequent crop (e.g., in the case of a N-fixing crop such as alfalfa or when a failed crop leaves residual fertilizer; Sweeney & Diaz, 2014). At the other extreme, a successful previous crop can deplete the soil profile of available N, increasing the nutrient response and use efficiency of a subsequent crop. The yield responses of subsequent crops due to these rotational effects can thus improve the efficiency of any fertilizer application (Pierce and Rice, 1988). In this context, several studies evaluated the effects of wheat on nutrient use efficiency in various cropping systems.

Including wheat in maize-based rotations can decrease maize N fertilization requirements for yield maximization through direct residue N returned to the soil, increased mineralizable N, and at least partly due to N rhizodeposition from wheat [i.e., N excretion from living plant roots (Deen et al., 2016)]. Taveira et al. (2020) found that 30% of N recovered by maize grain was derived from winter wheat and red clover residue, compared to 26% of soybean residual N. While red clover likely contributed to a large portion of the short-term N released in this study, wheat aboveground residue can also contain 10 to 80 kg N ha^{-1} that can be slowly mineralized and made available on the longer term (Fig. 1.4). Including wheat in a maize-soybean rotation improved maize N use efficiency and reduced N fertilization requirements to maximize maize yields (Gaudin et al., 2015a). Reduced N fertilization requirements may be attributed to greater soil mineralizable N when wheat is added to maize-soybean rotation, as demonstrated in two long-term experiments in Canada (Congreves et al., 2015). This is likely due to the high variability in wheat residue C:N ratio (Fig. 1.4H), reflecting the high variability in nitrogen percent in wheat residue (Fig. 1.4F), which can range 5.6-fold (Fig. 1.4F). Meantime, carbon percent ranged only 1.2-fold (Fig. 1.4G). Data from 149 winter wheat crops in Kansas revealed that for yield environments ranging from 1.6 to 4.0 Mg ha^{-1}, wheat residue returned to soil ranged from 2.4 to 10.1 Mg ha^{-1} and carbon returned to soil ranged from 1.0 to 4.1 Mg ha^{-1}, both increasing linearly with increases in yield. Increase in soil organic carbon (SOC) as response to N fertilization only occurred when wheat was included in a soybean system (Congreves et al., 2017). This is perhaps likely due to the high C content of wheat residue, which can range from 36 to 43% (Fig. 1.4G), returning as much as 4 Mg C ha^{-1} to the soil (Fig. 1.4C).

Beyond direct N return from wheat residue, it is estimated that up to 20% of total N assimilated by wheat can be deposited in the soil via rhizodeposition (Janzen, 1990; Wichern et al., 2008), which is largely attributable to its dense, fibrous root system (Muñoz-Romero et al., 2013). Janzen (1990) estimated that a wheat population of 200 plants m^{-2} released approximately 20 kg N ha^{-1} in rhizodeposits. Under rainfed conditions in a Vertisol, Muñoz-Romero et al. (2013) reported wheat N rhizodeposition of 93 kg ha^{-1} at a depth of 0-75 cm over a 2 yr period, representing 82% of belowground N.

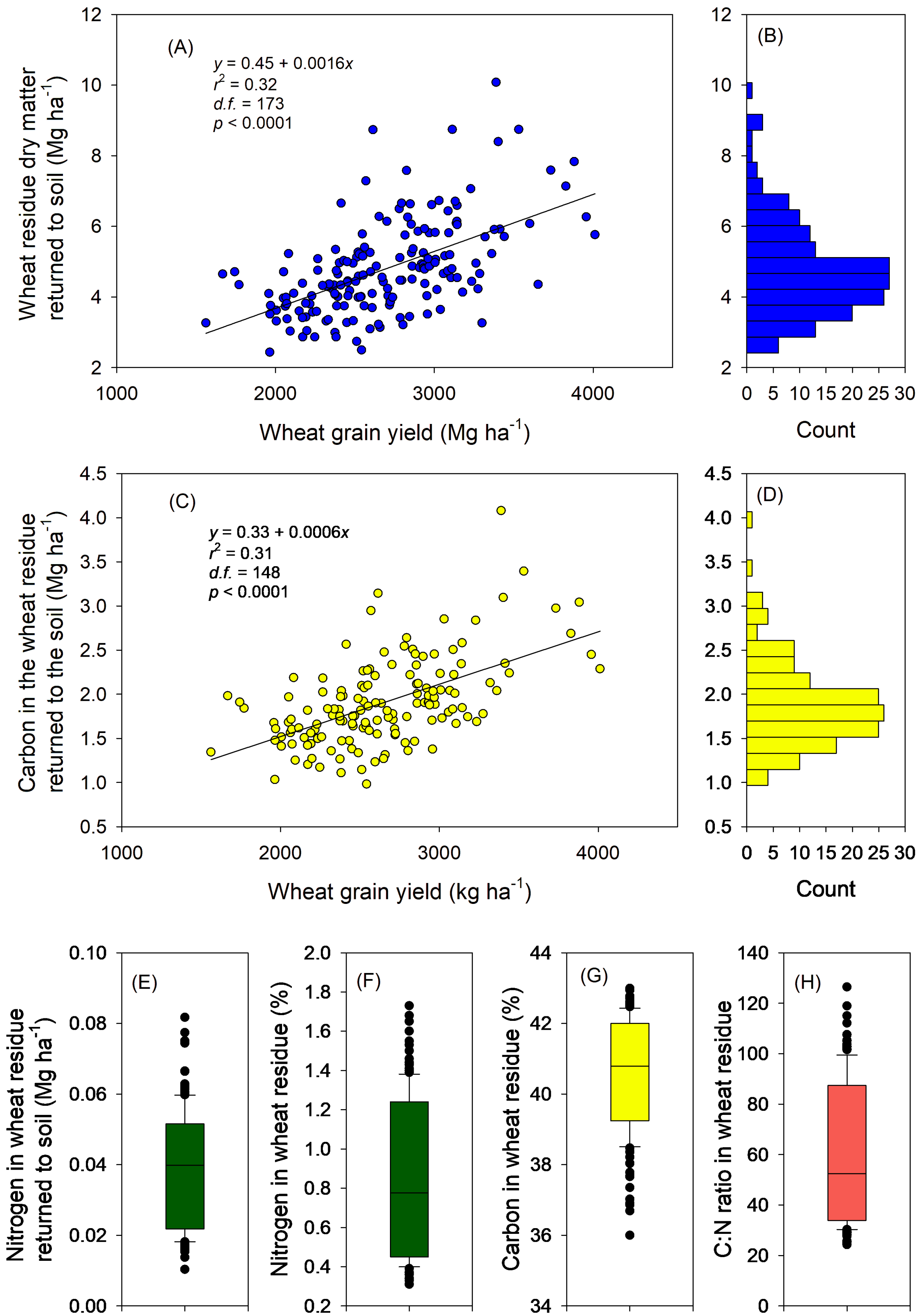
(A)
y = 0.45 + 0.0016x
r2 = 0.32
d.f. = 173
p < 0.0001
Wheat residue dry matter returned to soil (Mg ha-1)
Wheat grain yield (Mg ha-1)
(B)
Count
(C)
y = 0.33 + 0.0006x
r2 = 0.31
d.f. = 148
p < 0.0001
Carbon in the wheat residue returned to the soil (Mg ha-1)
Wheat grain yield (kg ha-1)
(D)
Count
(E)
Nitrogen in wheat residue returned to soil (Mg ha-1)
(F)
Nitrogen in wheat residue (%)
(G)
Carbon in wheat residue (%)
(H)
C:N ratio in wheat residue

Fig. 1.4 Wheat residue amount and composition across (A, B) 174 and a data subset of (C-H) 149 wheat crops in Kansas. Amount of (A, B) wheat residue, (C, D) carbon in the wheat residue, and (E) nitrogen in the wheat residue returned to the soil after wheat harvest as (A, C) function of harvested wheat grain yield. For details about data collection and processing, please refer to Bott et al. (2023).

In addition to N rhizodeposition, the dense roots of wheat plants can also recover leached N, as demonstrated by Hulugalle (2005) in an irrigated Vertisol in Australia, where N leached out of the root zone of cotton was subsequently recovered by wheat at 60 cm soil depth. In a 15-yr study in Illinois, Zuber et al. (2015) observed greater total N at 60 cm soil depth in a 3-yr maize-soybean-wheat rotation compared to a 2-yr maize-soybean rotation or continuous soybean, with intermediate values for continuous maize due to greater N inputs in maize-soybean-wheat and continuous maize compared to the maize-soybean systems. Additionally, the study revealed higher soil potassium levels for the 3-yr rotation compared to the 2-yr rotation (343 Mg ha^{-1} vs. 325 Mg ha^{-1}, respectively) due to greater potassium uptake by soybean compared to wheat. Similarly, soil extractable potassium, potentially mineralizable N, and total N were all greater with the inclusion of wheat in soybean systems because of the greater C input of wheat, accelerating microbial activity (Agomoh et al., 2020). Increased potassium use efficiency and potassium recycling also has been observed in cropping systems where maize and soybean were rotated with small grains, including wheat (Ambrosini et al., 2022). Greater C input of wheat and high C:N ratio variability plays crucial role accelerating microbial activity to make soil nutrients bioavailable (Agomoh et al., 2020).

Wheat offers an opportunity for improved phosphorus (P) fertilization efficiency of the entire crop rotation. The wheat phase of a rotation can be used to meet the P requirements of the entire cropping system, especially in no-tillage systems where P, an immobile nutrient, cannot be incorporated into the soil. Supplying P needs during the wheat phase can take advantage of the narrower row spacing of wheat drills (typically 10 to 25 cm) compared to a row crop planter (typically 45 to 90 cm) to distribute P more evenly across the soil surface. Furthermore, wheat has a higher critical soil test P level compared to crops such as maize and soybean, indicating that wheat is more responsive to P fertilization and makes more efficient use of the applied fertilizer (Sucunza et al., 2018). Wheat can tolerate high rates of P that can be safely applied in-furrow during sowing without harming the crop (Heard et al., 2014) at rates as high as 135 kg P_2O_5 ha^{-1} as dry fertilizer (Weber, 2021), which is sufficient for at least two or more subsequent crops. Therefore, wheat allows for application of surplus P that can later be used by following crops, whereas crops like maize and soybean are more sensitive to P at planting and require broadcast application of high P_2O_5 rates to avoid seed damage (Randall & Hoeft, 1988; Freilin et al., 2022). From an environmental perspective, injection of P fertilizer in the soil reduces the risk of runoff and water pollution (Smith et al., 2016) and application of P to winter wheat in the fall benefits from lower rainfall, which further reduces losses to runoff (Liu et al., 2022). Finally, wheat also offers opportunities to improve P management in highly weathered Oxisols. Here, some of the mechanisms may include the release of protons by wheat, increasing phosphate acquisition under low availability conditions (Wang et al., 2008). Additionally, wheat absorbs greater amounts of soil available P than other species such as chickpea, canola, cotton, and white lupin, *Lupinus albus* L. (Vu et al., 2010; Wang et al., 2008), due to a larger root system that allows it to explore greater soil volume. This helps to maintain the P in a biologically available form, preventing it from binding to highly available Fe and Al (Tiecher et al., 2015).

Wheat residue management for agronomic and ecological benefits

Wheat produces a significant amount of residue covering the soil and providing various agronomic and ecological benefits (Fig. 1.5). Wheat residue enhances soil water infiltration and intercepts a portion of incident solar radiation, lowering soil temperature and reducing evaporative losses. Reduced soil temperature can slow germination of weed seeds and provide a physical barrier that impedes weed emergence. This physical barrier also protects soil structure from the direct impact of rain drops, diminishing runoff and erosion, whether by water or wind. These benefits are reviewed in the following sections.

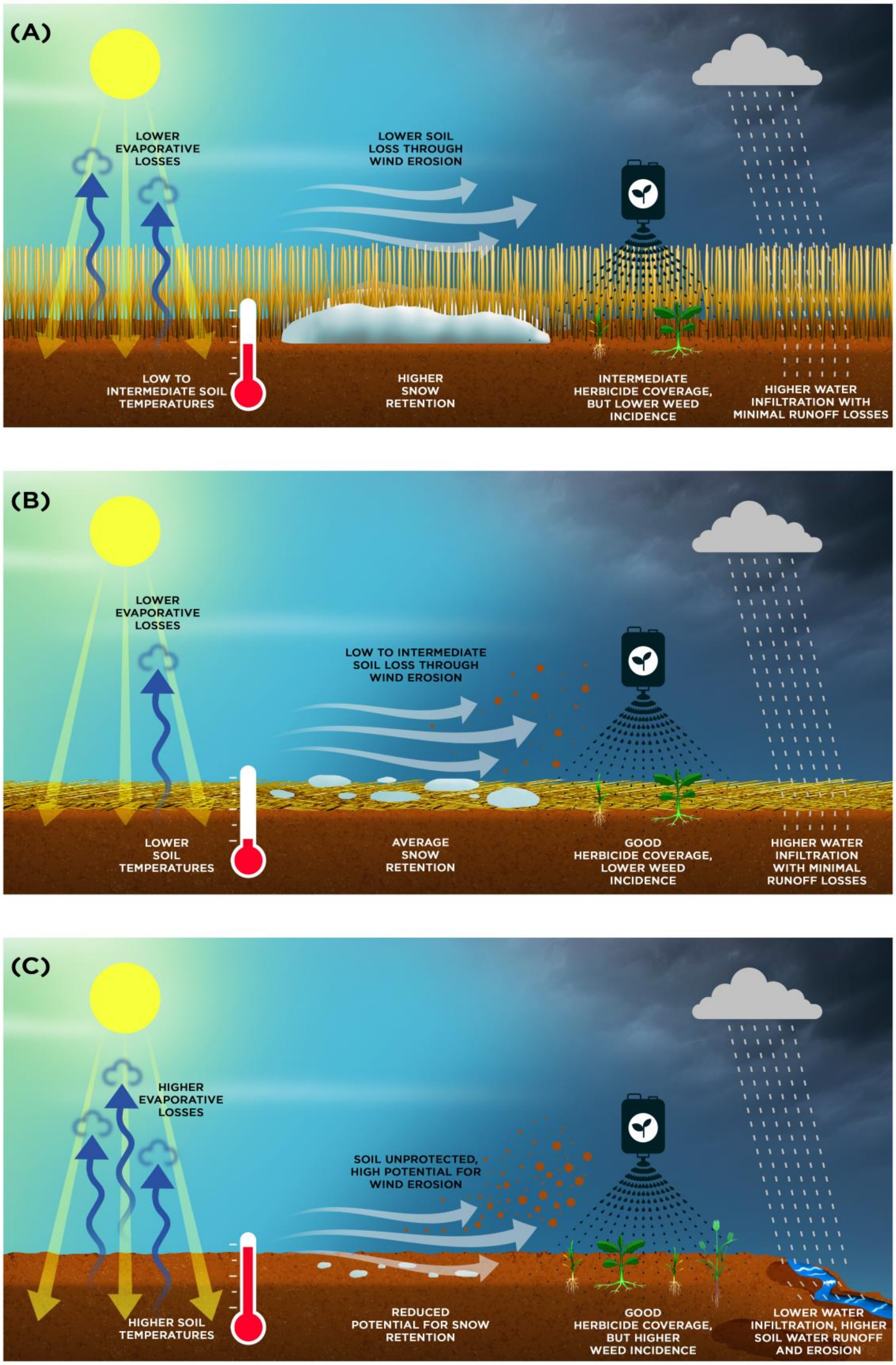
(A)
LOWER EVAPORATIVE LOSSES
LOWER SOIL LOSS THROUGH WIND EROSION
LOW TO INTERMEDIATE SOIL TEMPERATURES
HIGHER SNOW RETENTION
INTERMEDIATE HERBICIDE COVERAGE, BUT LOWER WEED INCIDENCE
HIGHER WATER INFILTRATION WITH MINIMAL RUNOFF LOSSES
(B)
LOWER EVAPORATIVE LOSSES
LOW TO INTERMEDIATE SOIL LOSS THROUGH WIND EROSION
LOWER SOIL TEMPERATURES
AVERAGE SNOW RETENTION
GOOD HERBICIDE COVERAGE, LOWER WEED INCIDENCE
HIGHER WATER INFILTRATION WITH MINIMAL RUNOFF LOSSES
(C)
HIGHER EVAPORATIVE LOSSES
SOIL UNPROTECTED, HIGH POTENTIAL FOR WIND EROSION
HIGHER SOIL TEMPERATURES
REDUCED POTENTIAL FOR SNOW RETENTION
GOOD HERBICIDE COVERAGE, BUT HIGHER WEED INCIDENCE
LOWER WATER INFILTRATION, HIGHER SOIL WATER RUNOFF AND EROSION

Fig. 1.5 Schematic representation of wheat residue management implications for soil, wind and water erosion control, soil temperature, soil water infiltration, snow trapping, herbicide spray deposition, and weed incidence with (A) standing wheat residue, (B) flat wheat residue, and (C) no wheat residue.

Residue for soil water conservation

Wheat residue reduced soil water evaporation by 4 to 25% compared to bare soil as biomass increased from 2.5 to 10 Mg ha^{-1} (Gava et al., 2013). Motazedian et al. (2019) studied the effects of wheat residue on sweet maize yield under moisture limitation (50, 70, and 100% of water requirement). They concluded that wheat residue improved yield in maize under water stress. The effectiveness of wheat residue for soil water conservation is a product of the number of stems m^{-2}, stem diameter, and stem height (Fryrear & Bilbro, 1994; McMaster et al., 2000). Thus, wheat residue management should focus on maximizing the number of stems m^{-2}, achieved via plant population or tillering (Bastos et al., 2020), and residue stem height post-harvest, because wheat stems are intrinsically slender. Wheat varieties also differ in stem composition, most varieties being hollow-stemmed, but some solid-stemmed, although this seems not to affect long-term residue persistence in the field or subsequent maize yields (Simão et al., 2021). Depending on the harvest method and cutting height, wheat straw residue can be either standing (*i.e.*, stubble oriented vertically) or flat (*i.e.*, stubble oriented horizontally on the soil surface). Standing wheat stubble fosters better water infiltration than maize stubble (Govaerts et al. 2007). Therefore, both the amount and orientation of wheat residue are important management considerations.

Standing versus flat residues differ in the degree to which they shade the soil surface from solar radiation, and thus in rates of energy exchange with the atmosphere (Bristow, 1988; Horton et al., 1996), with implications for the dynamics of soil water evaporation, soil temperature, and wind interactions with the soil surface (Fig.s 1.5A, B; Woodruff et al., 1972; Van de Ven et al., 1989; Fryrear & Bilbro, 1994).

For example, McMaster et al. (2000) reported that taller wheat stubble and higher plant populations reduced soil absorption of solar radiation and evaporation. Smika (1983) found that increasing wheat stubble height from 30 to 61 cm reduced wind speed at the soil surface by 74%, and Caprio et al. (1985) showed that standing wheat residue reduced soil water evaporation by 60%, although the reduction was environment-specific. Standing crop residue may permit greater soil water loss than flat residue in tropical environments due to greater penetration of solar radiation to the soil surface, leading to higher heat transfer and evaporation (Bristow, 1988). In such cases, the greater surface area shaded by flat residue minimizes soil temperature fluctuations and reduces soil water loss (Horton et al., 1996). However, in temperate environments with less solar radiation, standing residue may provide greater benefits by receiving slightly more direct solar radiation in the soil surface than flat residue (Bristow, 1988). Higher soil temperature can be beneficial in temperate no-tillage systems where low soil temperatures can delay germination and affect stand establishment (Unger & Stewart, 1976; Pittelkow et al., 2015). Black & Siddoway (1977) reported that wheat stubble cut to a height of 28 or 38 cm increased soil water content by 37% and 46%, respectively, at 0 to 60 cm depth compared to bare soil. In the semi-arid Great Plains of the US, Schlegel et al. (2023) reported a yield increase of ca. 10% and 5% for maize and grain sorghum, respectively, when these crops were planted into tall winter wheat stubble (43 and 64 cm) compared to short stubble (20 cm), attributing the yield increase to enhanced water use efficiency in taller stubble. However, no differences in fallow water accumulation, water use, or fallow precipitation efficiency were observed, suggesting that the advantage of taller stubble residue extends beyond off-season water storage. For example, in the semi-arid Canadian prairie, Cutforth et al. (2002) observed pronounced microclimatic differences near the soil surface between tall (25 to 36 cm) and short (15 to 18 cm) wheat stubble, with subsequent pulse crops exhibiting increased water use efficiency and better overall yields in taller stubble.

Plant population (i.e., number of stems m^{-2}), wheat stubble height, and row spacing can have variable effects on soil moisture across environments. In east-central Washington, US, Schillinger and Wuest (2021) observed that medium wheat stubble height (25 cm) conserved more soil water at the end of the fallow period than tall stubble (75 cm, 331 vs. 325 mm, respectively) at 0- to 180-cm soil depth. Tall stubble permitted more soil water loss due to higher levels of solar radiation reaching the soil surface. In contrast, in the southern Great Plains of Texas, US, tall wheat stubble (60 cm) resulted in 12% less irradiant energy at the soil surface and 26% less water loss compared to medium height stubble (40 cm), although soil water content was not directly measured (Baumhardt et al., 2002). Seeding rate and row spacing differed between these studies: Baumhardt et al. (2002) used 40 kg seed ha^{-1} and 30 cm row spacing compared to 55 kg seed ha^{-1} and 40 cm row spacing used by Schillinger and Wuest (2021). The contrasting results might be partially explained by greater residue height and narrower row spacing compensating for lower stem density in the former study. In another study in the semi-arid US Great Plains, soil water evaporation was reduced from 20 to 50% as wheat stubble height increased from 10 to 50 cm, the advantage becoming more apparent at higher plant populations (McMaster et al., 2000).

Soil water recharge from winter precipitation (liquid and snow) is important for subsequent crops in dry temperate environments (Grassini et al., 2010), and standing wheat stubble has a greater capacity to trap snow than flat stubble (Fig. 1.6; Black & Siddoway, 1977; Hoefer et al., 1981; Nielsen, 1998). Maximum snow retention capacity is impacted by stalk height, diameter, and soil surface area occupied by the stalk (Tabler and Schmidt, 1986); consequently, due to its density (stems per area), wheat straw has greater snow-catching capacity than sunflower, maize, canola, buckwheat, millet, *Panicum miliaceum* L., or sorghum (Merrill et al., 2007). Wheat residue stubble that is 15 to 19 cm, or 30 to 35 cm, can accumulate two and four times more snow, respectively, than bare soil (Aase & Siddoway, 1980). Over 10 winters in Saskatchewan, Canada, Campbell et al. (1992) measured about 1.6 times more snow in wheat residue that was 40-61 cm tall compared to 15-20 cm tall. Ries & Power (1981) suggested that for each 25.4 mm increase in stubble height, overwinter water storage increased by 6 mm due to greater snow trapping in North Dakota, USA. Although Black and Siddoway (1977) observed similar amounts of snow trapped by 28-cm and 38-cm stubbles, both trapped more than bare soil. Likewise, Caprio (1986) suggested that wheat stubble of 30-cm height was 30% more effective in harvesting snow than bare soil in Montana, USA. Standing wheat stubble trapped more snow than flat stubble in a winter wheat-maize-fallow crop rotation, translating into greater soil moisture and subsequent maize yield (Hoefer et al., 1981). The capacity of wheat straw to retain snow during winter fallow seems independent of wheat variety straw strength, as long as the straw remains standing through the winter (Simão et al., 2021).

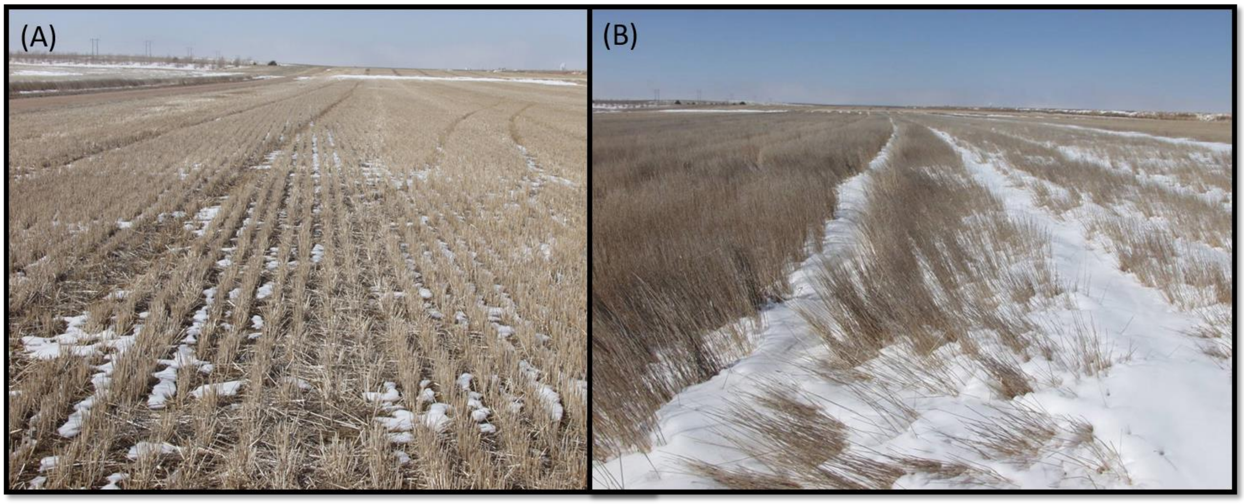

Fig. 1.6 Snow trapping potential of different winter wheat residue architectures. (A) Flat wheat residue, which results from harvesting the wheat crop using a conventional combine header with low or medium height positioning, has lower potential to retain snow than (B) standing wheat residue, which results either from harvesting the wheat crop using a stripper combine header or from harvesting it using a conventional header with high height positioning. Photos from nearby fallow fields taken in March 2004 near Akron, Colorado, USA. Photo credit and approval for publication: Dr. David Nielsen.

Residue for soil erosion control

Standing winter wheat residues are more effective in protecting soil from wind erosion compared to residues of cotton, forage sorghum, oilseed rape, *Brassica rapa* L., silage corn, soybeans, or sunflower (Lyles & Allison, 1981). Standing wheat stubble provides 6 to 9-fold better protection from wind erosion than standing sorghum or maize stubble due to its greater stem density (Lyles & Allison, 1976). Some evidence suggests that ca.110 standing wheat stems m^{-1} can reduce soil loss due to wind erosion by ca. 73% (Pi et al., 2020). Wheat stubble 15 to 19 cm tall can reduce wind passage 1.5-fold compared to bare soil at 9 cm above ground level, whereas stubble 30 to 35 cm tall can reduce it five-fold (Aase & Siddoway, 1980). The greater effectiveness of standing wheat residue in controlling wind erosion than flat residue results from its greater absorption of the wind's energy, raising the zero-velocity-point above the soil (Bilbro

& Fryrear, 1994; Siddoway et al., 1965). Therefore, wheat residue height, density, and orientation are all factors affecting soil loss by wind erosion during fallow periods (Fig. 1.5).

The use of wheat residue as a mulch can also reduce soil water erosion, runoff, and sediment concentration, while simultaneously increasing water infiltration and delaying runoff (Kavian et al., 2018; Lollato et al., 2012). In a sandy soil with a slope of 7.5%, wheat residue provided better soil coverage than soybean residue when an equivalent amount of biomass was present, and wheat residue was better at mitigating water erosion given an equal amount of soil coverage (Lopes et al., 1987). In a clayey Oxisol in a subtropical environment, wheat residue precluded soil erosion from high intensity rainfall events compared to a tilled area within the same field (Fig. 1.7; Lollato et al., 2012). Given similar amounts of biomass in the soil surface, wheat residue was better mitigating water erosion than corn residue, (Cogo, 1981; Laflen et al., 1981; Lopes et al., 1987; Wischmeier & Meyer, 1973). Rahma et al. (2019) observed effective water erosion control with as much as 4 t ha^{-1} wheat straw over a wide range of slopes (from 8.7 to 46.6%), rainfall simulator events (60 to 180 mm h^{-1}), and soil types (silt loam, clay loam, loam). Wheat crops can produce as much as ca. 10 Mg ha^{-1} of residue (Fig. 1.4), offering an unparalleled opportunity for erosion control as it increases in parallel with amount of wheat residue (Rahma et al., 2019).

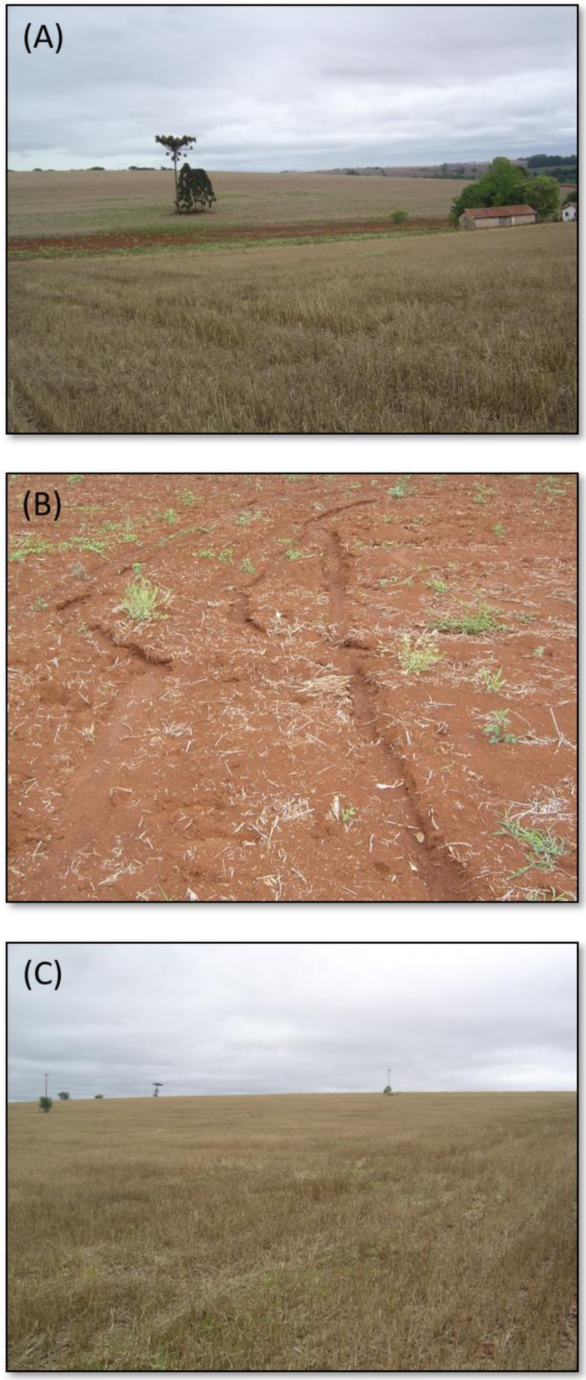

Fig. 1.7 Soil erosion prevention due to wheat residue in an Oxisol in a commercial farming operation in the subtropical climate of southern Brazil. (A) Distance photo of a small area where the soil was tilled to correct soil ruts from combine harvesting as compared to the remaining operation under no-till with large amounts of wheat residue in the soil surface. (B) Detailed photo of severe soil erosion resulting from a 100 mm h^{-1} rainfall event in the tilled area. (C) Detailed photo of an area neighboring to the photo in (B), showing no apparent soil erosion due to the surface wheat residue. The slope in this commercial operation ranged from null to 19% and averaged 7.5%. Photos taken in September 2007 near Tamarana, Parana, Brazil. Photo credit and approval for publication: Dr. Romulo Lollato. For more details, please refer to Lollato et al. (2012).

Overall, wheat stubble height of 25 to 45 cm provides a similar degree of soil moisture conservation (Black & Siddoway, 1977; Cutforth & McConkey, 1997; Schillinger & Wuest, 2021, Schlegel et al. 2023), wind and water erosion control (Fryrear & Bilbro, 1994), snow trapping (Black & Siddoway, 1977; Aase & Siddoway, 1980), and herbicide spray deposition on the soil (Simão et al., 2020) when compared to stubble heights greater than 45 cm. Although standing wheat residue is beneficial in temperate environments due to better snow trapping and increased solar irradiation of the soil surface, flat residues may be more beneficial in tropical environments because they keep soil temperatures cooler while reducing evaporation. Whereas detailed wheat residue management recommendations could be tailored to specific agronomic contexts (e.g., standing *vs.* flat, tall *vs.* short), the mere presence of any wheat residue provides numerous agronomic and ecosystem benefits relative to bare soil.

Residue for weed control

Wheat can aid weed management through diversification of crop rotations and via physical (residue barrier and shading) and chemical (allelopathic) effects of the wheat residue on weed germination, growth, and development, with the potential to reduce weed density and biomass in various cropping systems.

Including winter cereals in systems dominated by spring-annual rotations can reduce weed density and the system’s herbicide requirements (Beres et al., 2010a). This is especially true in seasons when winter cereals have good canopy development during the fall, well prior to the emergence of spring weeds, resulting in a greater competitive ability in the spring (Beres et al., 2010a). The competitive ability of the crop against weeds can be enhanced by in-season decisions that modify its canopy architecture (e.g., cultivar selection and seeding rates), reducing the need for spring herbicide applications and production of weed seed for establishment in subsequent crops (Beres et al., 2010b; Blackshaw, 1994; Thomas et al., 1994). For example, Li J. et al. (2019) concluded that including spring wheat as a break crop in continuous chickpea, or a chickpea-mustard-chickpea rotation, reduced weed density and biomass in the system. Here, wheat demonstrated both a better competitiveness and stronger allelopathic effects against weeds compared to chickpea.

Seedbank densities of smooth pigweed (*Amaranthus hybridus* L.), common lambsquarters (*Chenopodium album* L.), and annual ryegrass (*Lolium rigidum* L.) were lower after a wheat crop in a 3 yr maize-soybean-wheat rotation than after soybean in a 2 yr maize-soybean rotation (Teasdale et al., 2004). Whereas optimal weed management in continuous maize or in a maize-soybean rotation typically requires maximum herbicide rates, reduced herbicide rates (still within the recommended label rates) may afford a similar level of weed control in a maize-soybean-wheat rotation (Martin et al., 1991). For example, Schreiber (1992) observed reduced stands of giant foxtail (*Setaria faberi* L.) in a maize-soybean-wheat rotation compared to a maize-soybean rotation, regardless of tillage system. This effect was attributed to the allelopathic effects of wheat straw as well as the physical barrier and shading provided by the residue. These results indicate that including wheat in crop rotations can be an effective weed management tactic with the potential to reduce herbicide use and lower production costs.

Wheat residues left in the field post-harvest can reduce weed pressure due to effects on soil temperature and shading that, in turn, reduce both the germination of weed seeds and their subsequent growth rate (Crutchfield et al., 1986; Dhandat et al., 2023; Mahajan et al., 2018). In-season crop management decisions (e.g., population, row spacing, variety, etc.) can modulate residue production (Roth et al., 2021), consequently impacting weed management for subsequent crops. Other mulches may provide similar physical effects, but the high C:N ratio of wheat residue (average: 60; range: 24 to 126; Fig. 1.4), coupled with large amounts of biomass returned to the soil, can prolong these benefits in comparison to residues of other crops with lower C:N ratios, because the amount of residue seems to directly affect weed density and biomass (Crutchfield et al., 1986).

Wheat residues can reduce weed emergence, weed density, and weed yield due to allelopathic chemical effects (Elliott et al., 1978), toxic microbial products (Jilani et al., 2008; Aslam et al., 2017; Zuo et al., 2014), and pH changes in the soil (Kimber, 1973). Compared to other crops, wheat has a high potential for allelopathic weed control (Farooq et al., 2020; Table 1.1). Allelopathy comprises biochemical interactions between living organisms, including plants and bacteria, that can provide an eco-friendly form of weed control. Aslam et al. (2017) reported that wheat plants and decomposing residues release a variety of chemicals, including hydroxamic and phenolic acids, and short-chain fatty acids, which have allelopathic activity, providing allelopathic wheat cultivars with natural weed control potential. Allelopathy from wheat residues varies among wheat cultivars (Bott et al., 2023; Guenzi & McCalla, 1966; Kimber 1967; Prasanta et al., 2003; Wu et al., 2003) and among plant parts, such as between root and shoot (Villagrasa et al., 2006) and in the rhizosphere (Khaliq et al., 2011). Aerial components of the wheat plant exhibit the highest allelopathic activity, followed by the whole plant (roots plus shoots), and then roots (Zuo et al., 2005). In wheat seedlings, allelochemicals predominate in the roots, although weed suppression appears most effective during vegetative and post-harvest phases (Wu et al., 2000).

Table 1.1 Weed species exhibiting decreased seed germination following wheat plant extract application.

Scientific Name	Common Name	Extract Concentration	References
Abutilon theophrasti Medic.	Velvetleaf	5%	Steinsiek et al. (1982)
Amaranthus palmeri	Palmer amaranth	5%	Bott et al. (2023)
Amaranthus retroflexus L.	Redroot pigweed	10%	Blum et al. (2002); Flood & Entz (2009)
Cassia obtusifolia L.	Sicklepod	5%	Steinsiek et al. (1982)
Digitaria ciliaris (Retz.) Koeler	Southern crabgrass	10%	Li Z.R. et al. (2019)
Echinochloa crusalli var. frumetaceae (Roxb.)	Japanese barnyard millet	5%	Steinsiek et al. (1982)
Echinochloa crus-galli	Barnyard grass	5%	Steinsiek et al. (1982)
Ipomoea hederacea (L.) Jacq	Ivy-leaf Morning glory	5% and 10%	Steinsiek et al. (1982); Blum et al. (2002)
Ipomoea lacunosa (L.)	Oitted-morning glory	5%	Steinsiek et al. (1982)
Lolium perenne L.	Perennial ryegrass	50, 25, and 12.5%	Al Hamdi et al. (2001)
Lolium rigidum Gaud	Annual ryegrass	10%	Wu et al. (1998)
Sesbania exaltata (Raf.) Cory	Hemp sesbania	5%	Steinsiek et al. (1982)
Setaria faberi L.	Giant foxtail	5%	Bott et al. (2023)
Setaria viridis L.	Green foxtail	10%	Flood & Entz (2009)
Sida spinosa	Prickly sida	10%	Blum et al. (2002)

Significant correlations have been found between the allelopathic activity of wheat and soil microbial communities (Zuo et al., 2014). Analysis of soil microbial C and N indicate that wheat creates a microhabitat where microbes thrive, with elevated levels of key soil enzymes such as urease, catalase, sucrase, and dehydrogenase. Thus, cultivation of allelopathic wheat varieties can be an effective tool for environmentally sustainable weed management in cropping systems (Bott et al., 2023; Jabran et al., 2015).

Despite the physical and chemical benefits for weed control, wheat residue can reduce herbicide spray deposition on emerging weeds below the residue and on the soil surface compared to bare soil or to shorter residues, with spray deposition diminishing as a linear function of increasing stubble height (Crutchfield et al., 1986; Simão et al., 2020). Standing wheat straw may retain up to 60% of the applied herbicide (Ghadiri et al., 1984; Wicks et al., 1994). Simão et al. (2020) observed that post-emergence herbicide spray deposition on the soil decreased by 47% and 33% in the presence of tall (71 cm) and medium (36 cm) wheat stubble, respectively, compared to a bare soil control. Standing wheat stubble reduced post-emergence herbicide deposition by 52% on smooth pigweed (*Amaranthus hybridus* L.) when sprayer travel speed was 16 km h^{-1}, although deposition was enhanced by 14% when travel speed was reduced to 8 km h^{-1} (Wolf et al., 2000). Less than 43% of pre-emergence herbicides reached the soil surface when 2250 kg ha^{-1} of flat wheat residue was present (Banks & Robinson, 1982). Both standing and flat residue orientations can intercept similar amounts of herbicide when targeting the soil surface. However, flat residue is preferable if the target is the weed canopy. Despite interception of some spray droplets by wheat stubble, Black and Siddoway (1977) found that green foxtail (*Setaria viridis* L.) growth was reduced with increasing wheat stubble height and found 50% more water at 0 to 60 cm soil depth in taller stubble due to weed suppression. Thus, the disadvantages of standing compared to flat residue for herbicide spray deposition depend on the application target and may be offset by lower weed biomass accumulation.

Residue benefits for faunal diversity

Many wildlife species use wheat residue, and it can have a positive impact on bird populations by providing both food and nesting habitat, potentially supporting bird populations (Duebbert & Kantrud, 1987; Lokemoen & Beiser, 1997; Rodgers, 1983). Wheat stubble may offer better nesting cover for some species than other vegetation types, such as alfalfa or mixed grasses (Higgins, 1975; Snyder, 1984). Observations suggest that wheat may support greater bird populations than rice, and that various bird guilds favor different crop phenological stages that provide different habitat types (Kler & Parshad, 2011). For example, ring-necked pheasant (*Phasianus* colchicus), the most important upland game bird in parts of North America, can successfully nest and reproduce in wheat residue that is not tilled (Linder et al; 1960; Snyder, 1984, 1991). Likewise, various species of dabbling ducks nest in fields of no-tillage winter wheat in the prairie pothole region of North Dakota, US, with nest density averaging 6 to 8 nests per 100 hectares (Duebbert & Kantrud, 1987). Nest failures in this case seem to be primarily caused by mammalian predation, and no evidence suggested pesticide-related mortality. Although concerns exist about pesticide residues in wheat stubble, one recent study found that canary bird species preferred to feed from grain of conventionally grown wheat stubble compared to organic stubble, likely due to higher protein content in the grain from the former (McKenzie & Whittingham, 2010). In addition to providing nesting habitat, wheat residue also supports insect populations, which are an important food source for insectivorous birds that, in turn, often prey on insect pests in crop fields (Borad & Parasharya, 2018).

Soil

It can take up to 18 months for 80% of wheat residue to be mineralized in the field, and data shown in Fig. 1.4 supports previous findings that C returned to the soil can average 5.4 Mg ha^{-1} y^{-1} for ca. 11 Mg ha^{-1} of residue (Buyanovsky & Wagner, 1987). Wheat can improve SOC levels, due in part to the high lignin content of wheat residues, which decompose slower than those of maize or soybean, and play a crucial role in SOC accumulation (Broder & Wagner, 1988). A high C:N ratio of ca. 82 (though with a large variability driven by plant nitrogen status; Fig. 1.4) contributes to the slow decomposition rate of wheat residue (Truong & Marschner, 2019), which has a half-life that exceeds 100 days (Wenneck et al., 2022). Wheat is thus an appealing choice for soil mulching and improvement of SOC. Although continuous wheat had no significant impact on SOC levels in a recent meta-analysis (King & Blesh 2018), there was an increase in SOC when wheat was rotated with higher-biomass crops like maize. The context-specific effects of wheat on soil parameters are explored in this section.

Soil physical and chemical properties

Soil organic carbon has been widely accepted as a robust soil health indicator (Allen et al., 2011) and often shows a positive linear relationship with cereal crop yields (Oldfield et al., 2019) and crop yield stability (Gaudin et al., 2015b; Congreves et al., 2017). A 15-yr study in Illinois, US, compared soil properties of continuous maize, continuous soybean, a 2-yr maize-soybean rotation, and a 3-yr maize-soybean-wheat rotation and found that the 3-yr rotation including wheat resulted in the greatest water aggregate stability (0.87 kg kg^{-1}). In contrast, continuous soybean and maize-soybean rotation had the lowest (0.79 and 0.82 kg kg^{-1}, respectively). In this study, soil water aggregate stability was positively correlated with SOC. An 11-yr study of rotation and fertility on clay loam soil in Ontario, Canada, found that adding wheat to a maize-soybean rotation resulted in greater SOC and total N in the top 20 cm of soil (Congreves et al., 2017). Another long-term study in western Canada concluded that rotations including winter wheat stabilized soil organic matter, whereas rotations including legumes led to a loss of SOC in dry years (Campbell & Zentner, 1993). In a 27-yr study in eastern Kansas, US, cropping systems containing winter wheat (i.e., continuous winter wheat or a soybean-winter wheat rotation) resulted in higher levels of total soil C and N than continuous soybean or grain sorghum, or a 2-yr soybean-grain sorghum rotation (Doyle et al., 2004). Later, in the same experiment, Fabrizzi et al. (2007) found that after 29 yr, the greatest amount of soil organic matter at a 0-30 cm depth was associated with a high frequency of winter wheat in the rotation. According to Prior et al. (2005), a soybean-sorghum rotation that includes wheat under no-tillage has a higher potential for C sequestration and soil storage compared to a 2 yr soybean-sorghum rotation under conventional tillage practices. In cotton systems, SOC fractions, in particular lighter fractions, were higher when rotated with wheat rather than legumes (Conteh et al., 1998).

Other indicators of soil health include physical (e.g., soil structure, porosity, infiltration, and water holding capacity), chemical (acidity, electrical conductivity, and plant nutrient content), and biological parameters (e.g., microbial biomass and diversity) (Allen et al., 2011). Congreves et al. (2015) evaluated 15 soil health parameters across four long-term experiments lasting between 14 to 29 yr in Ontario, Canada and found that crop sequences including wheat had the highest scores for soil health and aggregate stability based on the Ontario Soil Health Assessment score, whereas rotations featuring solely maize and soybean had the lowest scores, results that were later confirmed by Wepruk et al. (2022) in the same field. In two studies spanning 19- and 23-yr periods, Van Eerd et al. (2014) demonstrated that indices of soil quality at 0 to 15 cm depth (i.e., total N, SOC, aggregate stability, and penetrometer resistance) increased with the frequency of winter wheat in the rotation, consistent with the findings of Andrews et al. (2004). In a 15-yr study in Illinois, Zuber et al. (2015) found that a maize-soybean-wheat rotation resulted in greater soil water aggregate stability compared to a maize-soybean rotation or continuous soybean, as more soil compaction (i.e., higher soil bulk density) occurred under continuous soybean, and more soil acidity resulted under continuous maize, likely due to high N fertilization. As indicated by decreased soil bulk density, lower soil compaction was also observed when one wheat cycle was added in the final year of a double maize-soybean rotation in a no-tillage system (Renwick et al., 2021). These authors also observed a correlation between SOC and reduced water stress in maize plants, suggesting that introducing small grain cereals or cover crops into maize-soybean rotation could enhance maize yield and increase its drought tolerance. Only 0.7 Mg ha^{-1} wheat residue significantly increased rain infiltration compared to bare soil in ridged, tilled soils (Baumhardt & Lascano, 1996). Furthermore, Agomoh et al. (2020) reported that water-extractable organic C, total C, and particulate organic matter increased in rotations that included a higher frequency of wheat. In cotton systems, wheat helped to mitigate compaction of a Vertisol in Queensland, Australia better than legumes (Hulugalle et al., 2008).

Soil microorganisms

Maize-based rotations under reduced tillage in a sandy loam soil in Michigan, US, had the greatest macro-aggregate stability when they included wheat, which was correlated with SOC, total N, and fungal abundance (Tiemann et al., 2015). Similarly, Tomlin et al. (1995) reported greater abundance of soil fauna and microflora when wheat was included in a maize-soybean rotation. The quantity of soil bacteria was 1.4 times greater when winter wheat interseeded with red clover was included in a maize-soybean rotation. However, microbial pathways leading to N_2O production, ammonia oxidization, and denitrification were also greater, likely due to greater soil microbial activity under the more diverse rotation (Linton et al., 2020). Studies of 21- and 36-yr periods in Ontario, Canada, found greater soil microbial activity and SOC (that was linearly correlated with yield) at 0-15 cm depth in maize and soybean rotations that included winter wheat, the difference being more apparent when winter wheat was interseeded with red clover (Chahal et al., 2021).

Soil carbon sequestration and greenhouse gas emission

Both current and previous crops must be considered when estimating greenhouse gas (GHG) emissions from agricultural fields. For instance, continuous maize produces three to five times greater annual N_2O emissions (2.6 kg N ha^{-1}) than continuous soybean (0.8 kg N ha^{-1}) or winter wheat (0.5 kg N ha^{-1}) (Drury et al., 2008). When maize followed maize, N_2O emissions were 60% higher than when maize followed winter wheat (2.6 vs. 1.6 kg N ha^{-1}; Drury et al., 2008). Crop type may have a greater impact on CO_2 emissions than the cropping system itself (Johnson et al., 2010). For example, spring wheat can emit less CO_2 per unit of grain produced (0.46 kg CO_2 kg^{-1} grain) compared to canola (0.80 kg CO_2 kg^{-1} grain), mustard, or flaxseed (0.59 kg CO_2 kg^{-1} grain), but more than chickpea, dry pea, or lentil (0.20 to 0.33 kg CO_2 kg^{-1} grain) (Gan et al., 2011). Furthermore, a study in eastern Canada found that N_2O emissions from wheat did not differ from soybean and alfalfa, although the source of N differed among crops (synthetic N vs. biological fixing-N) (Meyer-Aurich et al., 2006a).

The potential of a cropping system to sequester C and mitigate GHG emissions depends on the crop, the environment, and management, but wheat can serve as a C sink. Wheat can act as a C sink in certain cropping systems; with a net ecosystem exchange of -347 g C m^{-2}, similar to that of tallgrass prairie (Bajgain et al., 2018), and lower than that of soybeans (Veeck et al., 2022) or canola (Wagle et al., 2019). Wagle et al. (2019) found that wheat had a larger C sink potential than canola due to its better adaptation to high temperature and vapor pressure deficits, resulting in more efficient water and solar radiation use for C accumulation. Gan et al. (2011) concluded that spring wheat can act as a sink of CO_2 (ca. 0.03 to 0.4 kg CO_2eq kg^{-1} grain) on the semiarid Canadian prairies when associated with a decreased summer-fallow period, an improved N fertilization regime, and inclusion of a legume crop in the rotation. Afterward, Gan et al. (2014) reported that dryland spring wheat production sequestered carbon on average ranging from -29 to -634 kg CO_2 eq. ha^{-1} $year^{-1}$, depending on the cropping system. Winter wheat served as a C sink during the growing season (~ 370 g C m^{-2} removal) in the US southern Great Plains, regardless of whether it was grown for grain only, graze only, or dual-purpose, although grain-only removed the most C (Wagle et al., 2021). Likewise, Wang et al. (2022) suggested that the changes in soil organic carbon stock measured before wheat sowing and after harvest ranged from -187 to 780 kg ha^{-1} under chisel plowing and zero tillage in China. Even with 50% wheat straw removal under conventional tillage, a single wheat cycle in a 4 yr maize-maize-soybean-soybean rotation sequestered more SOC (23.9 vs. 21.4 g kg $soil^{-1}$) and total yearly C inputs (3,190 vs. 3,002 kg C ha^{-1} yr^{-1}) than a maize-maize-soybean-soybean rotation in a 37 yr study in Elora, Canada, with more pronounced benefits when wheat was interseeded with red clover (Meyer-Aurich et al., 2006a; King et al., 2020). In the North China Plain, He et al. (2022) reported that the change in soil organic carbon storage in the 0-30 cm soil layer ranged from -2.15 to 3.30 Mg ha^{-1} after one season of wheat cultivation, depending on tillage practices and residue management. Gan et al. (2011) estimated that an increase of 10% N use efficiency in wheat would reduce the C footprint of wheat by 7%, and by 13% if P-solubilizing and arbuscular mycorrhizal fungi were applied. In a 12 yr study in China, a maize plus wheat relay system had a 17.3% lower C footprint compared to monocrop maize (4,022 vs. 4,747 kg CO_2 eq ha^{-1} $season^{-1}$), and increased net economic return by 39.2% (Chai et al., 2021). However, no differences in GHG emissions were detected between a maize-soybean rotation versus a maize-soybean-wheat rotation in a study in Illinois, US (Behnke et al., 2018).

Wheat can produce more biomass with less N compared to maize, which should contribute to the accrual of carbon and low GHG emissions. Although wheat carbon accrual averages 17% less than maize due to lower biomass production (King & Blesh, 2018), its lower N requirement may still help mitigate climate change due to lower N_2O emission during the wheat growing season (Bronson & Mosier, 1993). Irrigated maize had greater N_2O emissions and less CH_4 fixation than either dryland or irrigated winter wheat in northeast Colorado, US, regardless of N management (Bronson & Mosier, 1993). In a no-tillage dryland system on sandy clay loam soil in eastern South Dakota, US, Lehman and Osborne (2013) found that a 4-yr maize-field peas-winter wheat-soybean rotation acted as a C sink, whereas a 2-yr rotation of maize-soybean was a source of greenhouses gases. In this study, the 4-yr rotation accrued 596 kg C ha^{-1} yr^{-1} in the top 30 cm of soil, while the 2-yr rotation lost 120 kg C ha^{-1} yr^{-1}. Later in the same study, Lehman et al. (2017) observed that daily N_2O emissions were 24% lower in the 4-yr rotation than in the 2-yr rotation (2.3 vs. 3.0 g N_2O ha^{-1} d^{-1}). The fibrous root structure of wheat, combined with the lower C:N ratio of field pea residue, may have contributed to SOC sequestration at greater depths in the 4-yr rotation (Buyanovsky & Wagner, 1987).

In Australia, rotations that included wheat improved cotton yield, mitigated declining soil quality, reduced emissions of CO_2 eq per unit area, and lowered CO_2 eq emissions per unit of cotton yield (Hulugalle et al., 2012). Modeling data from 2016 to 2100 in the context of climate change, predictions revealed that maize yield and SOC would increase in a maize-soybean rotation that included wheat, whereas a system relying solely on maize and soybean would not experience any increases (Jerecki et al., 2018), again highlighting the value of including wheat in corn-soybean rotations for climate change mitigation. Lastly, Chai et al. (2014) reported 35% less soil respiration when maize was intercropped with wheat compared to monocrop maize, with a concomitant reduction in CO_2 emissions. Crops that generate reduced GHG emissions or have greater potential for carbon sequestration are an opportunity to mitigate the contributions of agriculture to climate change. Therefore, including wheat in maize-soybean dominated systems has the potential to enhance soil health and cropping system resilience while simultaneously reducing N inputs and increasing carbon sequestration.

Benefits of wheat in mitigating biotic stresses

Diseases of commercial crops

Crop rotation is one of the most effective cultural practices for reducing the incidence and severity of soilborne diseases for most crops, potentially reducing the reservoir of soil inoculum or fostering an increase in microorganisms antagonistic to plant pathogens (Bockus & Shroyer, 1998; Krupinsky et al., 2002; Rupe et al., 1997). Factors influencing the efficacy of crop rotation in this regard include, but are not limited to, (i) the length of period between susceptible crop cycles (some fungal reproductive structures can survive in the soil for years without the presence of a host), (ii) the inherent genetic resistance of crop cultivars to specific diseases, (iii) the specificity of disease (some pathogens have wide host ranges), and (iv) other management practices (e.g., tillage, chemical treatments, etc.). Wheat can play an important role in breaking disease/pest cycles or reducing the incidence of certain diseases while still generating economic benefits (see sections 7 and 8).

Crop diversification can aid in reducing disease pressure, whereas monocultures and simple binary rotations can permit pathogens to build up in the soil (Liu et al., 2022). The soybean cyst nematode, *Heterodera glycines* Ichinohe (SCN), is a major threat to soybean production. Although results have been inconsistent, several studies suggest that the addition of wheat to soybean rotations can aid in SCN suppression. For example, fields where wheat preceded soybeans had a 30% lower SCN egg population compared to fallow, both at the start of flowering and at harvest (Rocha et al., 2021). Similarly, the addition of wheat to a soybean-sorghum rotation produced a substantial reduction in SCN compared to continuous soybean in a Kansas (US) study, although the effectiveness of this approach was inferred to depend heavily on the susceptibility of the soybean cultivar to SCN (Long & Todd, 2001).

The mechanisms behind the effects of wheat on SCN suppression have been the focus of discussions, with some studies suggesting that wheat residue, root exudates, and mechanical interference with host recognition can explain reduced SCN incidence in soybean fields preceded by wheat (Baird & Bernard, 1984). Wheat residue can lower soil temperature at soybean planting (see Section 5), and significant reductions in the density of SCN females and cysts can occur when soil temperatures dip below 26 °C (Anand et al., 1995). Rocha et al. (2021) suggested that wheat-induced shifts in the soil microbial community might aid in SCN suppression, as wheat appears to encourage the growth of fungi and bacteria that parasitize SCN cysts and eggs, such as *Mortierella*, *Exophiala*, *Conocybe*, *Rhizobacter* spp, microorganisms that are not observed in soybean fields preceded by fallow. However, a number of years of wheat–soybean rotation may be needed to obtain significant disease suppression, as the resting stages of SCN and other microorganisms can persist in soil for several years.

Changes in the soil microbial community caused by wheat residue decomposition (see section 6.2) can have an allelopathic effect on soil pathogens because the microbial communities can produce antimicrobial compounds or compete for resources (Peralta et al., 2018). Beneficial effects of wheat residue in reducing disease incidence in other crop rotations have been observed. For instance, wheat residues from a no-tillage cover crop reduced *Phytophthora* blight incidence on bell pepper to between 2 and 43%, compared to ~70% on bare soil, largely due to diminished splashing and aerial dispersal of the spores (Ristaino et al., 1997).

Including wheat as a break crop to maize-sugar beet, *Beta vulgaris* L., rotations in Europe suppressed the fungal pathogen *Rhizoctonia solani* (Kühn), a disease that causes root and crown rot in sugar beet, and increased sugar beet yield, with significant benefits even for cultivars with lower susceptibility (Buhre et al., 2009). Wheat has been tested as a 'rotation-breaking cereal' in pea, chickpea, lentil, and mustard, and has shown significant benefits in suppressing *Ascochyta* blight, an important disease of chickpea (Nene, 1982). Inclusion of wheat in canola rotations can reduce incidence of blackleg disease caused by *Leptosphaeria maculans*, a major disease of canola in Canada (Guo et al., 2005), improving seed quality and increasing yields by 5 to 57% (Kutcher et al., 2013).

Wheat rotations have also been evaluated to control white mold, *Sclerotinia sclerotiorum*, in soybean and canola. Gracia-Graza et al. (2002) showed a 50 – 75% reduction in the production of apothecia, white mold fruiting structures, in a wheat–soybean rotation compared to continuous soybean, even though no yield benefits were observed. Because *S. sclerotiorum* attacks a broad range of crops that are often rotated with soybeans (e.g., alfalfa, edible beans, peanuts, *Arachis hypogaea*, pulse crops, and sunflower), wheat can help suppress this disease in fields where it is present (Dorrance & Novakowiski, 2017; Paulitz et al. 2015). However, fungal propagules can be produced on non-host plants, and dormant structures such as schlerotia can persist in soils for extended periods, so several years of rotation with wheat (or other non-host crops) may be required to reduce inoculum levels in a field (Dorrance & Novakowiski, 2017; Fernando et al., 2004).

Benefits of adding wheat to continuous soybean or maize, or a soybean–maize rotation, have been reported for other soilborne pathogens that cause root rots and other diseases, including *Fusarium*, *Pythium*, *Drechslera*, and *Bipolaris* spp. (Gagnon et al., 2019; Govaerts et al., 2007). A 5-yr field experiment in the semi-arid, subtropical highlands of Central Mexico found a lower incidence of root rot and the nematode *Pratylenchus thornei* in maize grown in rotation with wheat compared to continuous maize under both no-tillage and conventional tillage treatments (Govaerts et al., 2007). Root rot incidence was lowest in a wheat–maize rotation under conventional tillage, whereas the incidence of *P. thornei* was lowest in a wheat–maize rotation under zero tillage. The effectiveness of crop rotation tactics for disease management always depends on the disease targeted, and in some cases, wheat can worsen disease losses in other crops. For example, adding wheat to a maize-soybean rotation increased the incidence of *Fusarium graminearum* (Marburger et al., 2015). Although fungicides helped to control the disease in maize-soybean-wheat and maize-wheat-soybean (harvested as silage) rotations, they were not effective in continuous wheat, or in maize-wheat-soybean rotations (not harvested as silage). In this case, the greatest benefits of fungicides were obtained in rotations without wheat.

Root exudates, produced either by wheat plants or by an interaction of wheat residues with the following crop, have been implicated as one mechanism of disease suppression. Root exudates include simple sugars, organic acids, and amino acids released from living plant roots into the soil that influence the composition and function of soil microbial communities (Grigulis et al., 2013). Because this community affects plant-microbe interactions, it also mediates plant disease dynamics (Kessler & Baldwin, 2002; Van Poecke et al., 2001). For example, intercropping fava bean with wheat decreased the production of several root exudates that facilitate infection of fava bean by *Fusarium* wilt disease compared to a bean monocrop (Li et al., 2020). The reduced production of root exudates in the wheat–fava bean intercrop resulted in lower *Fusarium* wilt incidence in fava bean and higher root dry weight.

The beneficial effects of wheat rotations for horticultural crops have also been explored. Apple replant disease is a significant problem in replanted apple orchards, *Malus domestica* Borkh, and is caused by soilborne fungal pathogens (Winkelmann et al., 2019). Greenhouse studies in Washington, US, have shown that apple seedlings planted into soils previously used to grow wheat grew better compared to those planted in soils that were not sown with a previous wheat crop (Gu & Mazzola, 2003; Mazzola & Gu, 2000), an improvement attributed to reduced root infections by *Rhizoctonia* and *Pythium* fungi, and fewer *Pratylenchus* spp. nematodes. The bacterial communities inhabiting the soil and the apple rhizosphere varied across treatments, indicating the potential of wheat root exudates to influence the soil microbial community. The authors also noted varying effects of different wheat genotypes on apple seedling growth.

Wheat as a source of beneficial insects

Crop rotation and diversification practices tend to enhance natural pest control services, also referred to as 'conservation biological control' in agricultural systems (Brust & King, 1994; Rusch et al., 2014). Wheat fields host many herbivorous arthropods that represent important food sources for generalist predators and parasitoids in early spring when these species begin to emerge from winter diapause or hibernation (e.g., Michaud & Qureshi, 2005; Tauber & Tauber, 1973). These beneficial species have their initial spring generation in winter wheat and then emigrate from the maturing crop in vast numbers to colonize summer crops, where they contribute important biocontrol services (Michaud, 2018). Provided pesticide applications do not disrupt natural biological control processes, most wheat herbivores rarely exceed economic thresholds, because wheat can compensate for considerable defoliation and other forms of arthropod damage during vegetative stages (prior to the critical stage) without significant effects on yield. For example, a study in central Kansas, US, found that grain yields remained close to average values even in plots heavily grazed by army cutworms, *Euxoa auxilaris* (Grote), at densities that reached 100 larvae per m^{-2} (Michaud et al., 2006). Aphids, in particular, are an important food source for many families of generalist predators, including Anthocoridae, Chrysopidae, Coccinellidae, Nabidae, and Syrphidae, among others (Brodeur et al., 2017). On the US Great Plains, wheat hosts many aphid species, including *Rhopalosiphum padi* (L.), *Schizaphis graminum* Rondani, *Sitobion avenae* (F.), *Diuraphis noxia* (Kurdjumov), *Sipha maydis* Passerini, and *Metopolophium* spp., among others. The same biological traits that can make aphids such formidable pests when their biological control is disrupted, excellent colonization ability and a high reproductive rate, facilitated by asexual reproduction and a telescoping of generations (live birth of pregnant daughters), also render them a reliable and robust food supply for many arthropod predators early in the season when few other preys are abundant in the agricultural landscape. Wheat fields have also been identified as a source of spiders (Aranae), ground beetles (Carabidae) and rove beetles (Staphalinidae) (Booij & Noorlander, 1992). The movement of insect predators from neighboring crops can be a more important determinant of their population density than their numerical responses within the crop itself (Kieckhefer & Miller, 1967). Thus, in temperate regions, winter wheat is a critical spring 'nursery' crop for beneficial species that later migrate to summer crops where they contribute to biological control of many potential pests (e.g., Lopez & Teetes, 1976; Rice & Wilde 1988; Prasifka et al., 1999; Colares et al., 2015).

Economics

Selection of a suitable crop rotation scheme can be challenging as it involves the management of tradeoffs between crop yields and yield stability to maintain profitability and sustainability over time. Although wheat can increase the yield of rotational crops such as maize and soybean (see section 3), it may also lower net returns when wheat is less profitable than other crops (Zacharias & Grube, 1984; Singh et al., 2021). This effect, combined with changes in government policies and programs in North America (Anderson et al., 2001), has recently increased the area of maize and soybean at the expense of wheat (Rosenzweig & Schipanski, 2019), although others have noted increased profitability and decreased variability in net returns result when wheat is included in the rotation (Farno et al., 2002; Keim et al., 2003; Kyei-Boahen & Zhang, 2006). Helmers et al. (2001) identified three distinct ways crop rotation can reduce economic risk: (i) diversification, in which low returns from one crop are balanced by relatively high returns from another; (ii) lower yield variability of rotations compared to continuous culture; and (iii) higher overall crop yields and reduced production costs of rotations. Wheat can provide all of these benefits because it provides yield benefits of crop diversification (see section 3), lower annual yield variability, and a lower production cost than maize or soybean.

Because wheat can be harvested as grain, high-quality forage, or both (e.g., dual-purpose wheat), can be double-cropped with summer crops (see section 3.1), and can have its residue sold for profit, its economic benefits should be assessed within the entire portfolio of farm income. Both field and modeling studies have indicated that grazing wheat offers an opportunity to increase net returns, provided grazing is terminated prior to the onset of the critical period (Redmon et al. 1996; Fieser et al., 2006; Moore et al., 2009; Taylor et al. 2010). Studies in Oklahoma, US, showed that double-cropping soybean with a dual-purpose winter wheat provided the highest average net return, followed by a simple double-crop soybean-wheat system, and lastly by monocrop soybean (Farno et al., 2002; Keim et al., 2003; Kyei-Boahen & Zhang, 2006). These studies found lower variability in annual net returns in rotations that included winter wheat due to more stable net returns that resulted from more stable yields. Alternatively, in years with low wheat prices or environments where wheat residue limits summer crop development due to cooler soil temperatures (see section 3.5), wheat straw can be removed and sold as hay to increase system profitability (e.g., Roth et al., 2021). Maize and soybean systems that include wheat can have similar or greater net return when wheat straw is sold, as observed in New York, US (Singer & Cox, 1998b; Katsvairo & Cox, 2000a), New Jersey, US (Singer et al., 2003), and Quebec, Canada (Gagnon et al., 2019).

A few studies have reported greater net returns from rotations consisting of maize and soybean only, mainly due to the higher profitability of these crops (Zacharias & Grube, 1984; Singh et al., 2021). However, Janovicek et al. (2021) showed that adding winter wheat to a maize-soybean rotation every 4 to 5 years can lead to greater long-term net returns and lower risks of revenue reduction while providing the sustainability and environmental benefits of crop diversification. Similarly, Meyer-Aurich et al. (2006b) observed that a maize-soybean-wheat rotation consistently provided higher and more stable net returns (by \$30 to \$64 ha^{-1}) compared to continuous maize or a maize-soybean rotation, and was less sensitive to increasing energy costs. In comparison, although the profitability of continuous maize was the highest in some cycles, it was the lowest in most cases. Incorporation of wheat into a maize crop rotation can reduce the variance of net returns when costs are variable (Peterson et al., 1991). Although the mean returns over variable costs may be slightly lower in a rotation that includes wheat, farmers may wish to minimize risk by accepting a lower potential return in exchange for a more consistent one. In Kansas, US, a rotation of grain sorghum and winter wheat has been preferred by moderately risk-averse producers, whereas monocrop winter wheat or grain sorghum has been preferred by the more risk-averse (Williams et al., 2000).

The optimal rotation clearly depends on region, climate, and management practices. In a study in Brazil, Garbelini et al. (2022) found that replacing second-crop maize with wheat in two out of four years of a rotation cycle resulted in a higher cumulative profit, as second-crop maize often yielded negative returns. In the Mississippi Valley, US, double-cropped soybean-wheat rotations can yield higher net return per unit of irrigation water when monocrop soybean does not cover production costs (Wesley & Cooke, 1988). The monetary return per unit of irrigation water was higher for a double-cropped soybean-wheat system than for monocrop soybean ($29.28 vs. $17.77 per 25.4 mm) (Wesley et al., 1991). Including wheat in irrigated cotton systems in Australia resulted in higher average gross margins per unit of irrigation water compared to a cotton monocrop (Hulugalle & Scott, 2008) and required half the irrigation water (Farrell et al., 2008). Moreover, cotton systems were more profitable than monocrop cotton when rotated with wheat, fava beans, or dolichos, *Lablab purpureus* (Hulugalle et al., 2002).

Concluding remarks

The area under wheat cultivation has decreased in various regions of the world due to the expansion of summer crops that, on their own, may seem more profitable. Here, we provided evidence of a wide range of benefits specific to wheat and explained its benefits within various cropping systems. Wheat offers a range of tactical and strategic flexibilities that can benefit farming operations and reduce their environmental footprint. Wheat can increase overall grain yields and decrease yield variability of other crops in a rotation. In less complex cropping systems, adding of wheat can enhance agroecosystem diversity, improve the resilience of cropping systems against biotic and abiotic stresses, and reduce the input requirements of other crops. When available, we emphasized the underlying biological mechanisms generating these benefits; however, we note that many of these are not yet well understood, originating a number of research opportunities to explore the synergistic effects of wheat on cropping system productivity and resilience beyond mere grain production. Promising traits warranting further investigation include the allelopathic potential of wheat against weeds, increased N availability through rhizodeposition, and improvement of the composition and longevity of wheat residues. Because wheat often acts as a net carbon sink, policy development could encourage its adoption to potentially aid in mitigating agricultural contributions to climate change. The diversification of simple crop rotations by incorporating wheat should be stimulated to foster a more sustainable and resilient agriculture with the potential to feed a growing population while reducing its environmental impacts.

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Chapter 2 - Crop rotation and tillage impact yield performance of soybean, sorghum, and wheat

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Abstract

The benefits of no-till to crop yield depend on environment and crop sequence; thus, understanding their interactions is a long-term process. This 44-yr field experiment examined grain yield, yield stability, and adaptability of continuous winter wheat (*Triticum aestivum* L.) (Ct-WT), continuous soybean (*Glycine max* (L.) *Merrill*) (Ct-SY), continuous grain sorghum (*Sorghum bicolor* (L.) *Moench*) (Ct-GS), soybean-winter wheat rotation (SY-WT), and soybean-grain sorghum rotation (SY-GS) under three tillage systems (NT = no-tillage; RT = reduced tillage; CT = conventional tillage) near Ashland Bottoms, KS. The temporal variation across the studied years allowed us to evaluate treatments under low- and high-yielding environments. Crop rotation consistently out-yielded continuous cropping and the advantage was enhanced when integrated with NT. Yield stability decreased under NT continuous cropping in most systems. Wheat was adaptable to low- and high-yielding environments with similar grain yield and yield stability among treatments, except for NT Ct-WT, which had the lowest yield stability and grain yield (2.5 *vs.* 3.5 Mg ha^{-1}). Soybean grain yield was greater under rotation than Ct-SY (2.7 *vs.* 2.0 Mg ha^{-1}) and under NT than RT and CT (2.6 *vs.* 2.4 Mg ha^{-1}), with similar yield stability. Soybean grown after wheat was more adaptable to low-yielding environments and grown after sorghum to high-yielding environments. Sorghum in NT SY-GS was adaptable to low- and high-yielding environments and had the greatest yield (6.2 Mg ha^{-1}) and yield stability. This long-term

study demonstrated the advantages of crop rotation combined with NT for grain yield, yield stability, and crop adaptability.

Introduction

Increasing agricultural production while simultaneously meeting sustainability and conservation goals is a challenge that farmers and researchers face to meet the projected food demand for a growing population (Cohen, 2002). Adopting practices that are considered part of a "conservation agriculture" system may help meet this goal while protecting natural resources (Giller et al., 2015). However, recent evidence suggests that individual practices within conservation agriculture may not always result in improved crop yield (Pittelkow et al., 2015). Thus, there is a need to quantify under which conditions certain conservation agriculture practices may benefit the system through improved crop yield or yield stability.

Conservation agriculture is a system characterized by practices including crop rotation, minimal soil disturbance [i.e., no-tillage (NT) or reduced-tillage (RT) systems], and permanent soil cover, as well described by Hobbs et al. (2008). Several studies showed the beneficial impacts of crop rotation on the environment (e.g., increased biodiversity and carbon sequestration; Piorr, 2003; Leteinturier et al., 2006; Bowles et al., 2020; West and Post, 2002), soil health (Abreu et al., 2011; Karlen et al., 2006); and disease, weed, and pest suppression (Liebman and Dyck, 1993; Thenail et al., 2009). Recent evidence also suggests crop rotation and diversification can increase agricultural resilience under extreme growing conditions (Bowles et al., 2020). At issue here is an increasing trend toward monocropping in the first decade of the 2000's in the central US (Plourde et al., 2013), primarily led by economics and allowed by genetic advances (i.e., pesticide- and insect-resistant crops, drought-tolerant crops, etc.) and agricultural intensification (i.e., accessibility to resources such as pesticides, fertilizers, and irrigation), resulting in the deliberate application of pesticides, synthetic fertilizers, and water to maintain high yields. The increasing monocropping area was recently evidenced by a survey suggesting that as many as 51% of winter wheat (*Triticum aestivum* L.) fields in central Kansas (US) are monoculture (Jaenisch et al., 2021).

Conventional-tillage (CT) has been used in agriculture for fertilizer incorporation, weed control, and seedbed preparation. However, CT negatively impacts soil quality by lowering water-stable aggregation, soil organic carbon (SOC), soil microbial biomass, and soil nutrient availability, and increasing soil loss (i.e., erosion) (Jackson et al., 2003; Lollato et al., 2012; Karlen et al., 2013, Van Eerd et al., 2014). Thus, agriculture has shifted towards NT systems (Derpsch et al., 2010). Soil and water conservation are essential to sustain productivity, and the residue present on the soil surface plays an essential role in reaching this objective. Long-term conservation agriculture through NT and increased soil residue cover can increase water infiltration rate (Bissett and O'Leary, 1996; Bombino et al., 2019) and enhance precipitation storage by up to 35% as biomass residue increases (Nielsen, Unger, and Miller, 2005). Therefore, adopting NT practices in water-limited environments can positively impact crop yields by enhancing soil water conservation in dryland cropping systems (e.g., Farooq et al., 2011; Rusinamhodzi et al., 2011; Pittelkow et al., 2015; Schlegel et al., 2019a).

In water-limited environments where dryland cropping systems are adopted, the efficient use of water is essential for crop production. Precipitation use efficiency (PUE; crop yield per unit of growing season precipitation) is directly affected by crop sequence due to the length and timing of crop presence in the field and the precipitation received during this period, and also by the tillage system owing to its effects on crop yield and soil moisture retention (Peterson et al., 1996; Peterson & Westfall, 2004). Managing PUE can be the key to a dryland cropping system's success. However, PUE is a function of crop yield and growing season precipitation; thus, the concept of precipitation allocation (PA; the ratio of precipitation received during the growing season over the total precipitation during the entire crop rotation cycle) can complement the analysis of PUE in rainfed agriculture (Peterson & Westfall, 2004; Patrignani et al., 2019). Crop sequence directly affects PA, and cropping systems with shorter fallow periods and greater diversity and intensity can enhance PUE and PA (Peterson et al., 1996; Patrignani et al., 2019).

Despite the benefits of NT to different aspects of the production system, research has also shown drawbacks depending on environmental conditions and cropping system management (Giller et al., 2015). The lack of yield improvement in the first few years after NT adoption is often attributed to a "transitional period" (Derpsch et al., 2010) in which some benefits of NT – such as soil OM accumulation – have not yet been fully realized (e.g., Paustian et al., 1997; Abreu et al., 2011). Additionally, in a meta-analysis evaluating the long-term effect of conservation agriculture on maize (*Zea mays* L.) grain yield, Rusinamhodzi et al. (2011) found that cover mulch led to waterlogging and decreased yield in areas with an annual rainfall greater than 1000 mm. Many literature reviews have also shown that high amounts of residue on the soil left by NT could reduce crop yields due to a decreased soil temperature at planting in colder climates, increased time for crop establishment, and slower crop development (Kravchenko and Thelen, 2007; Ogle et al., 2012). Also, a shift in the weed population, mostly from broadleaves to grass weeds, and an increase in disease and insect pressure that survive in crop residue and soil are typical in NT systems (Thenail et al., 2009, Giller et al., 2015). All these factors can lead to yield reductions in some environments even though the concepts of conservation agriculture have been thoroughly communicated and encouraged worldwide (Giller et al., 2015).

One way to verify the long-term potential of conservation agriculture is through yield stability analysis in long-term studies (e.g., Raun et al., 1993; Silva et al., 2021). Yield stability refers to the ability of a crop to change its performance as environmental conditions change (Becker and Leon, 1988; Tollenaar and Lee, 2002), and it can be either a positive trait (e.g., a more stable system that sustains acceptable yield levels under below-optimal conditions such as drought, improving a system's sustainability) or a negative trait (e.g., a more stable system that does not capitalize on above-optimal conditions when these occur, detrimental to the sustainability of a system). The latter is usually captured by adaptability analysis that describes under which environmental conditions (e.g., high- *vs.* low yielding environments) a given crop management or genotype was more adaptable (Finlay and Wilkinson, 1963). Yield stability analysis is usually performed for different genotypes (Eberhart and Russell, 1966) but can also be applied to evaluate performance and predictability of cropping systems or fertilizer management strategies (Heinrich et al., 1982; Raun et al., 1993; Stelluti et al., 2007; Grover, Karsten and Roth, 2009; Gaudin et al., 2015; St. Luce et al., 2020; Xu et al., 2019). Analysis of yield stability can reflect the aforementioned positive and negative effects of rotation and tillage practices, helping to evaluate the long-term effect of cropping systems on crop yield. Yield stability is a simple way to explain treatment × environment interactions (Stelluti et al., 2007) but requires a relatively large number of environments, either through long-term experiments (thus, temporal variation in environments) or through experimental replication at different locations (thus, regional variation in environments).

Long-term studies can help to understand the effects of different tillage systems and their interaction with crop rotation across years, also potentially highlighting the role of crop yield stability to system's sustainability. Thus, our main objective was to compare the grain yield of winter wheat, soybean [*Glycine max* (L.) *Merrill*], and grain sorghum [*Sorghum bicolor* (L.) *Moench*] – three important crops in central US – as impacted by the interaction of crop rotation and tillage systems. Specifically, we were interested in the yield response to crop rotation and tillage systems in low- and high-yielding years, crop adaptability to different temporal environments, crop yield stability, PUE, and PA. Our secondary objective was to compare soil organic carbon (SOC) changes among different tillage practices at different periods.

Material and Methods

Long-term experiment and data source

Data used in the current study have been partially explored in previous studies (Peterson, 1981; Doyle et al., 2004; McVay et al., 2006; Fabrizzi et al., 2007; Godsey et al., 2007; Peterson and Roozeboom, 2007; Yin et al., 2010) which described the experimental setup in detail. The focus of these studies was primarily on soil health (i.e., physical, chemical, and biological properties) – which differs from our objectives – and, in some instances, on crop yield. The most recent manuscript that included crop yield resulting from the same field experiment was published in 2007; thus, we added another 11 years of grain yield data to previous reports.

Site description

This research was conducted from 1974 through 2018 (44-yr) at the Kansas State University Agronomy Farm near Ashland Bottoms (Riley County; 39°'07'N, 96°'37'W), KS, US.

Most of the experimental area was located on a Muir silt loam (fine-silty, mixed, mesic Cumulic Haplustoll), with a small portion located on a Reading silt loam (fine, mixed, mesic Typic Arguidoll). We note, however, chemical and physical proprieties (i.e., soil pH, cation exchange capacity, and particle size) of both soils were not significantly different (Doyle et al., 2004), and thus we would not expect the different soil series to influence the outcome of the analyses. The experiment was established under rainfed conditions with average annual precipitation from 1974 through 2018 of 850 mm, ranging from 460 to 1100 mm. This range is similar to that experienced across different geographies in the state of Kansas (Lollato et al., 2017; 2020a). Daily maximum and minimum air temperature and 24-hour precipitation were taken from the daily Global Historical Climatology Network (Menne et al., 2012) from 1974 to 2018.

Experimental design, treatments description, and general study management

The experiment was arranged as a split-plot design with four replications where crop sequence was the whole plot and tillage practices the subplots. Winter wheat, soybean, and grain sorghum were arranged in five crop sequences combined with three tillage systems. The crop sequences were continuous winter wheat (Ct-WT), continuous soybean (Ct-SY), continuous grain sorghum (Ct-GS), soybean-winter wheat rotation (SY-WT), and soybean-grain sorghum rotation (SY-GS). Crop rotations × tillage practices were duplicated in the experiment so each crop was harvested yearly to eliminate the potential confounding effect of annual variation on crop yield.

The cycle length for each crop sequence was considered as the number of years that involved one growing season for each crop present in the rotation, so all the crop sequences were 2-yr cycles. For SY-WT rotation, wheat was sown as soon as soybean was harvested, and soybean was planted in the year following wheat harvest. All crop sequences had a winter-fallow period (7 months), except Ct-WT, which had a summer fallow period (4 months), and SY-WT with a winter- and spring-fallow period (10 months). The intensity rate reflects the product between the number of crops grown in a crop rotation cycle and the respective crop's score (USDA pre-defined score based on crop water demand) divided by the unit of land area (USDA, NRCS 2013). The diversity rate is the frequency of appearance of a given crop type (grass, broadleaf, summer/winter crops, etc.) in the crop rotation length (USDA, NRCS 2013). The intensity rate for all crop sequences was 2, except for Ct-WT which was 1. The diversity rate for SY-WT and SY-GS rotation was 0.5, for Ct-WT was -0.5, and for Ct-SY and Ct-GS was -1.0.

The tillage systems consisted of NT, RT, and CT. In the NT treatment, crops were planted directly into the residue of the previous crops, fertilizer was not incorporated, and weed control was exclusively chemical. In RT plots, the soil was disked one to two times in the spring, and the field was field-cultivated before each crop planting to incorporate broadcast fertilizer, control weeds, and prepare the seedbed for planting. The CT plots were similar to RT plots but with an average of two extra tillage operations during the fall after crop harvest. Tillage for RT and CT treatments also varied year-to-year as needed depending upon environmental conditions. The only exception was for wheat in the SY-WT rotation, in which both RT and CT consisted of one tillage before wheat sowing due to the short period between soybean harvest and the sowing of the subsequent wheat. Thus, the difference between RT SY-WT and CT SY-WT treatments is that there were only one to two extra tillage practices before soybean.

Subplots containing each combination of crop sequence and tillage were 6.1 m wide and 18.3 m long. Wheat was sown at 90 kg ha^{-1} in 20-cm row spacing. Sorghum was planted at

162,500 seeds ha^{-1}, and soybean was planted at 312,500 seeds ha^{-1}, both in 76-cm row spacing. Varieties and hybrids changed during the study so that modern genotypes with good disease and insect tolerance were always adopted in combination with recommended seed treatments. Despite changes in the genotypes along the 44-yr of the study, each treatment had the same variety/hybrid planted within any given year to eliminate so that all treatments evaluated the same genotype, eliminating the confounding effect of genotype on treatment performance. Herbicide application varied year-to-year depending on weed population and new technologies that became available over the years. Foliar fungicides or insecticides were not applied during any time of the experiment. Fertilizers were applied according to university fertilizer reports recommendations based on soil test analysis, except for nitrogen and phosphorus. The same amount of fertilizer (112 kg N ha^{-1} yr^{-1} and 11.5 kg P ha^{-1} yr^{-1} of urea-diammonium phosphate mixture) was broadcast before each crop planting to reduce the impact of different amounts of nitrogen and phosphorus applied in the crop sequences (Godsey et al., 2007). This would not be a typical farmer practice for soybean; however, uniform, adequate fertilizer applications were implemented at the beginning of the experiment to eliminate fertility as a limiting variable for the evaluated systems. Wheat yields were based on a 1.83-m swath harvested from the center of each plot. Soybean and sorghum yields were harvested from each plot's fifth and sixth rows representing a 1.52-m swath width.

Statistical analysis

Mean crop grain yield in each treatment was calculated as the grain yield average across replications. Mixed model analysis of variance (ANOVA) was performed to compare the treatment effect on crop yield using PROC GLIMMIX procedure on SAS 9.4 software (SAS

Institute, Cary, NC), with crop sequence and tillage system as fixed effects and years as random effect. These analyses were performed across the 44-yr of the study but also independently for high-yielding years (i.e., annual crop's mean yield greater than 66^{th} percentile) and low-yielding years (i.e., annual crop's mean yield below 33^{rd} percentile) for each crop.

Crop adaptability and yield stability

Yield stability and adaptability analyses were performed as the linear regression of annual mean yield for each treatment against the environmental index (i.e., annual crop's mean yield of each treatment minus crop's grand mean yield across all years-treatments), as described by Eberhart & Russell (1966). While adaptability and stability analyses were initially created to investigate the interaction between crop genotype and environment, these indices can also be applied to evaluate different agronomic treatments (Piepho 1998; Reckling et al., 2021) as widely done in the literature (Grover, Karsten and Roth, 2009; Gaudin et al., 2015; St. Luce et al., 2020; Xu et al., 2019). The adaptability of each treatment in different yielding environments can be described by the slope of the regression (α), so $\alpha > 1$ reflects adaptability in high yielding environments, $\alpha = 1$ indicates broad adaptability, and $\alpha < 1$ reflects adaptability in low yielding environments. Meanwhile, a stable crop sequence and/or tillage system attains a treatment-environment coefficient of determination of the regression close to one (i.e., $r^2 \sim 1$). The intercept (β) reflects the average grain yield of the treatment. Regression analysis for adaptability and stability was performed using the REG procedure on SAS 9.4 software (SAS Institute, Cary, NC). Paired-comparison Student *t*-tests were used to analyze differences in α and β coefficients between treatments within the same crop, and $\alpha \neq 1$ was evaluated by the confidence interval of 95%. Because genotypes varied over the years for the three crops in this study, we checked for potential time trends in genotype-specific stability and adaptability by first clustering our data into periods based on when genotypes were modified each crop over the years. Second, we performed the individual linear regression analyses as described above for each period and crop's respective treatments (following ANOVA's significant effects). The resulting slopes for each treatment-by-period combination were plotted against time and compared for significant differences (Supplementary Fig. 1, Fig. 2, Fig. 3). Since only 6 out of 180 slope comparisons were significantly different over the years (for comparisons within crops across time periods), we are confident to proceed with the analysis using overall yield of 44-yr. Finally, we calculated cumulative yields as a function of crop cycle to determine the production advantage of a given tillage-rotation combination across the entire study period. Both of these analyses respected the ANOVA results across the 44-yr of study.

Precipitation use efficiency and allocation

Growing season was defined as the months of mid-October to mid-June for wheat and mid-May to mid-October for soybean and sorghum. The ratio of total grain yield of a specific treatment (kg ha^{-1}) and the precipitation (mm) during growing season of all crops in the treatment defined PUE. The ratio of rainfall each treatment received during the growing season of all crops in the rotation over the total precipitation during the entire rotation cycle defined PA. Student *t*-tests were used to define differences in PA and PUE between treatments. In this paper, the significance level of a given hypothesis test is set at 0.05

Soil organic carbon

The means for SOC from previous studies of the same experiment (Peterson, 1981; Doyle et al., 2004; Sarto, data not published, 2018) were retrieved to evaluate the changes in SOC over the years for NT, RT, and CT across the five crop sequences at the 0-5 cm depth.

Results

Environmental conditions

Wheat growing season precipitation ranged from 225 to 727 mm, with an average of 460 mm (Supplementary Fig. 4). During the summer-crop growing season, precipitation ranged from 270 to 920 mm, with an average of 470 mm. The mean minimum temperature ranged from -0.1 to 4.8 °C for wheat and 14.5 to 18.3 °C for summer crops during their respective growing seasons. Meanwhile, mean maximum temperature ranged from 11.6 to 18.3 °C for wheat and 27.5 to 30.1 °C for summer crops. No significant relationship between crop yield and precipitation was detected for any crops in the study (data not shown).

Grain yield, crop adaptability, and yield stability

Winter Wheat. Grain yield ranged from 0.1 to 6.9 Mg ha^{-1} across treatments and years. The crop sequence × tillage interaction significantly impacted yield across the 44-yr evaluated and in low-yielding years (Table 2.1, Fig. 2.1). In these two groupings, NT Ct-WT yielded as much as 35% less than the remaining treatments (2.5 vs. 3.2 to 3.4 Mg ha^{-1}). In high-yielding years, both main effects of crop sequence and tillage system were significant (Table 2.1, Fig. 2.1), with CT yielding similarly to RT, but both yielding more than NT (4.6, 4.6, and 4.1 Mg ha^{-1}, respectively). Additionally, wheat in rotation with soybean yielded more than Ct-WT (4.6 vs. 4.3 Mg ha^{-1}, respectively) (Table 2.1, Fig. 2.1).

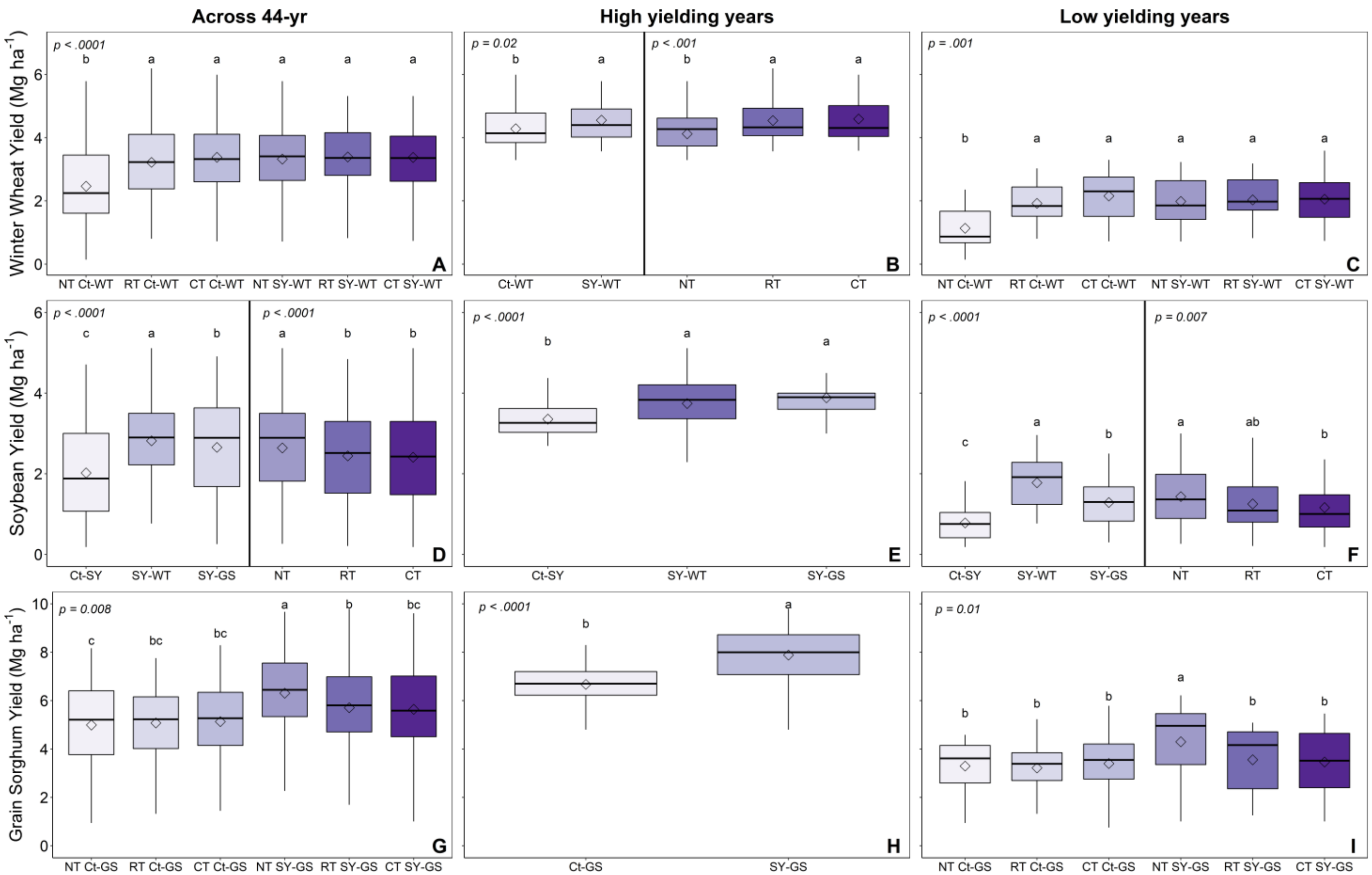

Fig. 2.1 Grain yield of winter wheat (A, B, C), soybean (D, E, F), and grain sorghum (G, H, I) under five crop sequences (Ct-WT = continuous winter wheat; Ct-SY = continuous soybean; Ct-GS = continuous grain sorghum; SY-WT = soybean-winter wheat rotation; SY-GS = soybean-grain sorghum rotation) and three tillage system (NT = no-tillage; RT = reduced tillage; CT = conventional tillage) across a 44-yr study (A, D, G), and in high yielding years (B, E, H) and low yielding years (C, F, I) among the 44-yr study (1974-2018) near Ashland Bottoms, KS, USA. High-yielding years represent crop's mean yield greater than 66th percentile, and low-yielding years represent crop's mean yield less than 33rd percentile over the 44-yr study. Boxplots with the same letter are not statistically different according to HSD test (F values significant at $p < 0.05$), and only the significant effects for each crop are shown.

Table 2.1 Analysis of variance (ANOVA) of winter wheat, soybean, and grain sorghum, under different tillage systems (T) and crop sequences (CS) in high yielding years (HY), low yielding years (LY), and across 44-yr from a long-term study (1974-2018) near Ashland Bottoms, KS, USA.

	HY (*n* = 14)[1]			LY (*n* = 14)			Across 44-yr (*n* = 44)		
	Winter wheat	Soybean	Grain sorghum	Winter wheat	Soybean	Grain sorghum	Winter wheat	Soybean	Grain sorghum
	p-value[2]								
T	0.0027	0.4186	0.7526	0.0040	0.0079	0.0178	<0.0001	<0.0001	0.1071
CS	0.0245	<0.0001	<0.0001	0.2928	<0.0001	0.2753	0.0004	<0.0001	<0.0001
T x CS	0.0873	0.9310	0.3280	0.0012	0.7747	0.0135	<0.0001	0.2399	0.0088

[1]High yielding years represent crop's mean yield greater than 66th percentile, and low-yielding years represent crop's mean yield less than 33rd percentile.
[2]F values significant at $p < .05$.

Crop adaptability and yield stability analysis are depicted in Fig. 2.1A. Wheat had a slope equal to one for all crop sequence × tillage combinations, suggesting broad adaptability across environments irrespective of crop sequence or tillage system. The lowest yield stability occurred for NT Ct-WT compared to all other treatments ($r^2 = 0.71$ versus $r^2 > 0.81$). Tillage (i.e., RT and CT) slightly improved yield stability in Ct-WT. The low stability of NT Ct-WT was even more apparent when comparing the intercept of the equations, as the intercept for RT and CT was significantly greater than NT ($\beta = 3.21$ and 3.37 vs. 2.46 Mg ha^{-1}, respectively), indicating greater overall mean yields for RT and CT. When wheat was rotated with soybeans, there was low variation about the fitted line and the slope was close to one, suggesting that SY-WT had wide adaptability and greater stability across different environments, regardless of tillage. The intercept of SY-WT was consistently greater than for Ct-WT, except for CT Ct-WT, which out-yielded all the other treatments. The cumulative yield analysis for wheat (Fig. 2.3A) showed NT Ct-WT only accumulated 105 Mg ha^{-1} across the 44 years, while all the other treatments accumulated around 140 Mg ha^{-1}.

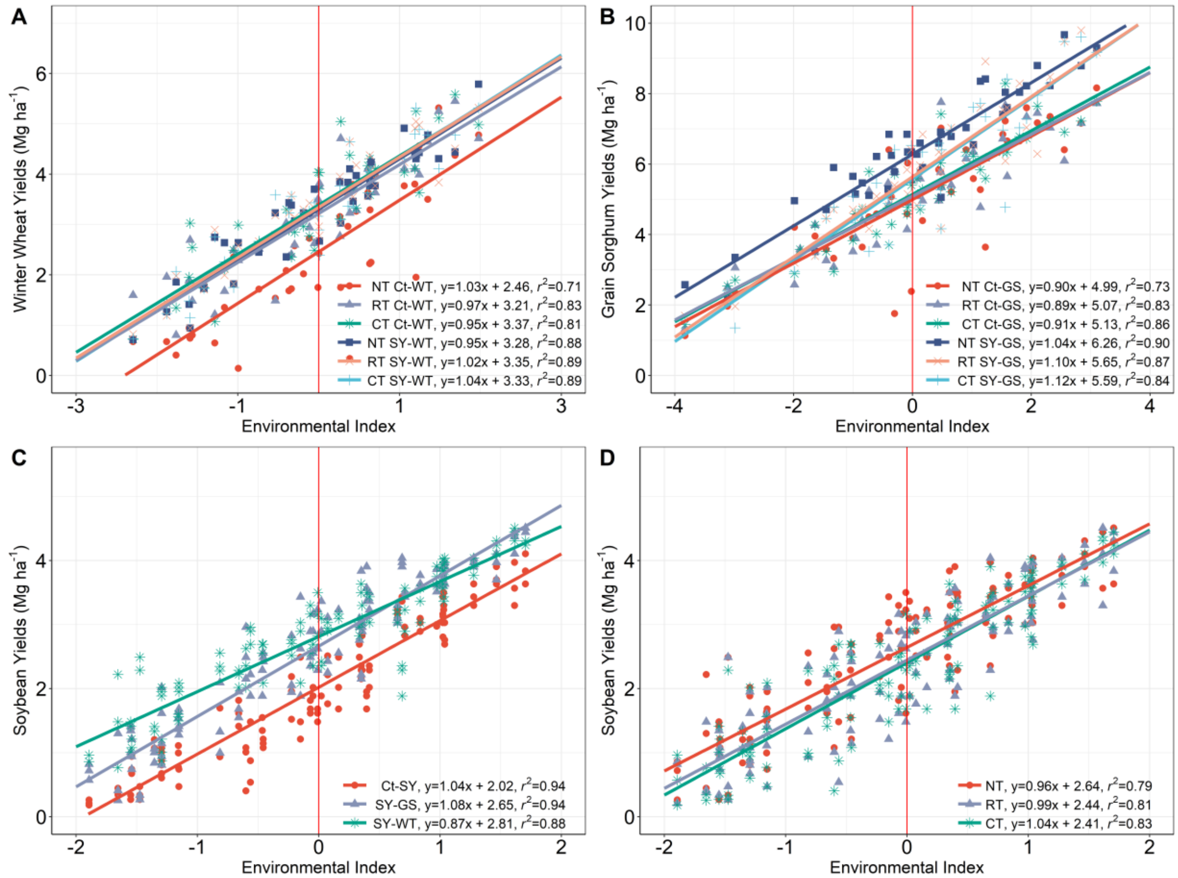

Fig. 2.2 Linear regression relationship between crop yield and the environmental index for yield of winter wheat (A), grain sorghum (B), and soybean (C & D) under different tillage systems (NT = no-tillage, RT = reduced tillage; CT = conventional tillage) and crop sequences (Ct-WT = continuous winter wheat; Ct-SY = continuous soybean; Ct-GS = continuous grain sorghum; SY-WT = soybean-winter wheat rotation; and SY-GS = soybean-grain sorghum rotation) in a 44-yr study (1974-2018) near Ashland Bottoms, KS, USA.

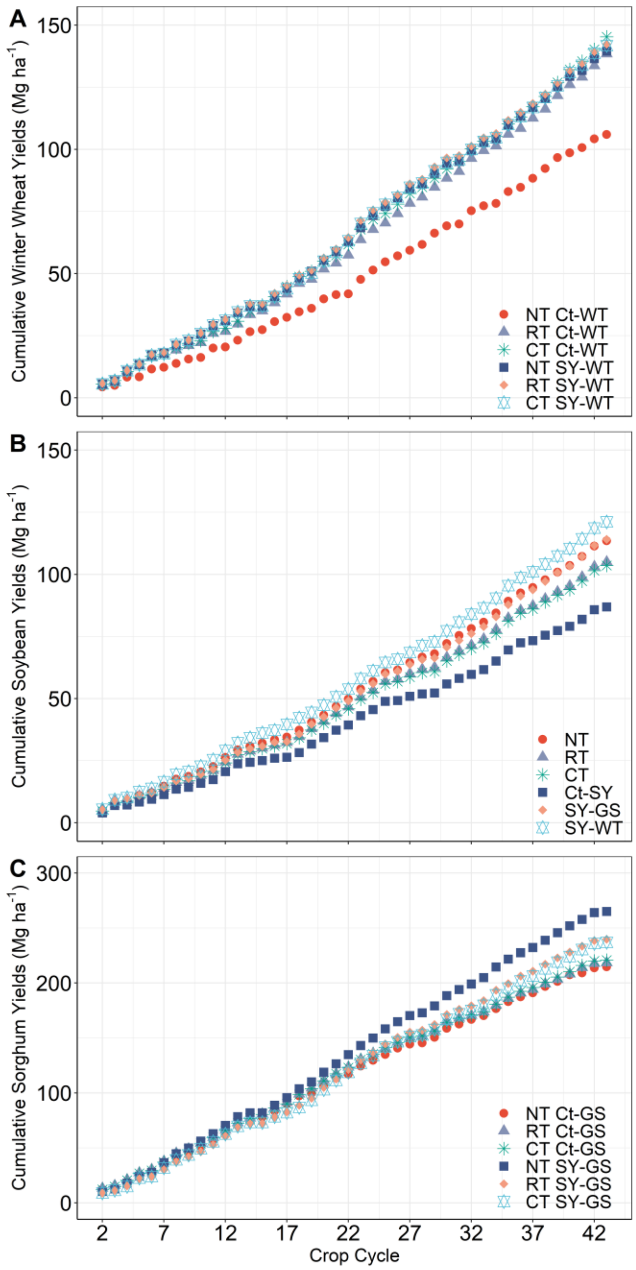

Fig. 2.3 Cumulative yield analysis for winter wheat (a), grain sorghum (b), and soybean (c) under three tillage systems (NT = no-tillage, RT = reduced tillage; CT = conventional tillage) and five crop sequences (Ct-WT = continuous winter wheat; Ct-GS = continuous grain sorghum; Ct-SY = continuous soybean; SY-WT = soybean-winter wheat rotation; SY-GS = soybean-grain sorghum rotation) in a 44-yr study (1974-2018) near Ashland Bottoms, KS, USA.

Soybean. Grain yield ranged from 0.2 to 5.1 Mg ha^{-1} across treatments and years. The main effects of tillage system and crop sequence were significant across the 44-yr and in low-yielding years, whereas only crop sequence was significant in high-yielding years (Table 2.1,

Fig. 2.1). Across 44-yr, NT yielded more than RT and CT, but the last two did not differ (2.6 vs. ca. 2.4 Mg ha^{-1}, respectively). Results were similar in low-yielding years, except RT did not differ from NT or CT. Soybean yields were significantly greater for SY-WT, followed by SY-GS, and Ct-SY (2.8, 2.6, and 2.0 Mg ha^{-1}, respectively), reflecting a yield increase of 16% to 27% when soybean was in a rotation with either sorghum or wheat. For high-yielding years, soybean yield in rotation with either wheat or sorghum (SY-WT and SY-GS) did not differ, but both were greater than Ct-SY.

Crop adaptability and yield stability analysis for soybean yields are depicted in Fig. 2.2C and 2.2D. Crop sequence (Fig. 2.2C) and tillage system (Fig. 2.2D) analyses were performed separately due to the lack of significant interaction in the ANOVA across the 44-yr (Table 2.1). Regarding crop sequences, Ct-SY showed a slope equal to one and low variation about the fitted line (i.e., r^2 close to one), suggesting monocropping soybean had broad adaptability and high stability over time. However, we note the Ct-SY treatment did not exploit high-yielding environments, which agreed with our ANOVA results for high-yielding years. This can also be noted by a significantly lower intercept for Ct-SY than SY-WT and SY-GS (β = 2.02 vs. 2.66 and 2.82 Mg ha^{-1}, respectively), suggesting lower overall yield levels. Soybean after wheat showed a slope significantly less than one, while SY-GS showed a slope significantly greater than one, and both slopes differed. This result indicates SY-WT was better adapted to low-yielding environments, whereas SY-GS had better adaptability to high-yielding environments. Both rotations showed low variation about the fitted line, indicating that their yields were stable across years. Regarding the tillage system, soybean yields were broadly adaptable ($\alpha \sim 1$) and stable ($r^2 \sim 1$) across environments under the three tillage systems. The cumulative yield analysis (Fig. 2.3B) showed SY-WT rotation had the greatest yield accumulated over the years (120 Mg ha^{-1}), followed by SY-GS (115 Mg ha^{-1}), while Ct-SY had the lowest yield accumulated in the 44th year (87 Mg ha^{-1}). The NT system had the greatest yield accumulated compared to RT and CT (115 vs. ca.105 Mg ha^{-1}, respectively).

Grain sorghum. Grain yield of sorghum ranged from 0.6 to 9.8 Mg ha^{-1} across treatments and environments during the 44-yr study period. The crop sequence × tillage interaction significantly affected yield across 44-yr of the study and in low-yielding years (Table 2.1). In both cases, NT SY-GS treatment had the highest yield compared to all other treatments (6.3 and 4.2 Mg ha^{-1} across 44-yr and in low-yielding years, respectively). Sorghum mean yields were greater in SY-GS rotation than Ct-GS, regardless of the tillage system, and were enhanced with less intensive tillage practices. In high-yielding years, the crop sequence main effect was significant (Table 2.1), in which SY-GS had significantly greater yield than Ct-GS.

Crop adaptability and yield stability analysis are depicted in Fig. 2.2B. For Ct-GS and SY-GS, slopes did not differ statistically from one, meaning sorghum grain yields are widely adaptable across different environments in both crop sequences. Sorghum grain yield stability was the greatest for the NT SY-GS treatment, having the least variation about the fitted line (greatest r^2), followed by RT and CT. The lowest yield stability across environments occurred for NT Ct-GS. The cumulative yield analysis (Fig. 2.3C) showed SY-GS had greater yield accumulation over the years compared to Ct-GS across tillage systems (215 to 220 vs. 237 to 265 Mg ha^{-1}), and the advantage was more apparent when associated with NT system (265 Mg ha^{-1}).

Precipitation use efficiency and precipitation allocation

More intense crop rotations increased PA (Fig. 2.4A). Precipitation allocation over the 44-yr was significantly lower for Ct-WT (51 ± 1 %, summer-fallow, intensity rate 1.0) than for rotations involving one or two summer crops such as Ct-SY, Ct-GS, SY-GS (PA = 63 ± 1 %, winter-fallow, intensity rate 2.0), and SY-WT (65 %, winter- and spring-fallow, intensity rate 2.0). Precipitation allocation ranged from 39 to 64% for Ct-WT, 49 to 75% for SY-WT, and 49 to 74% for crop sequences involving two consecutive years of summer crops.

Precipitation use efficiency for soybean was greater for NT than CT within all crop sequences, and NT was greater than RT in Ct-SY and SY-GS rotation (Fig. 2.4B). Overall, rotational crop sequences showed greater PUE than continuous cropping in soybean and sorghum (Fig. 2.4B and 2.7D). Wheat had similar PUE among all treatments, except NT Ct-WT had the lowest PUE (5.7 vs. > 7.5 kg ha^{-1} mm^{-1}). No significant differences in PUE were observed for wheat in the SY-WT rotation, regardless of the tillage system (ca. 7.5 kg ha^{-1} mm^{-1}). Sorghum had similar PUE among all treatments, except NT SY-GS was greater than RT and CT within SY-GS (14.3 kg ha^{-1} mm^{-1} for NT vs. 12.6 kg ha^{-1} mm^{-1} for RT and CT).

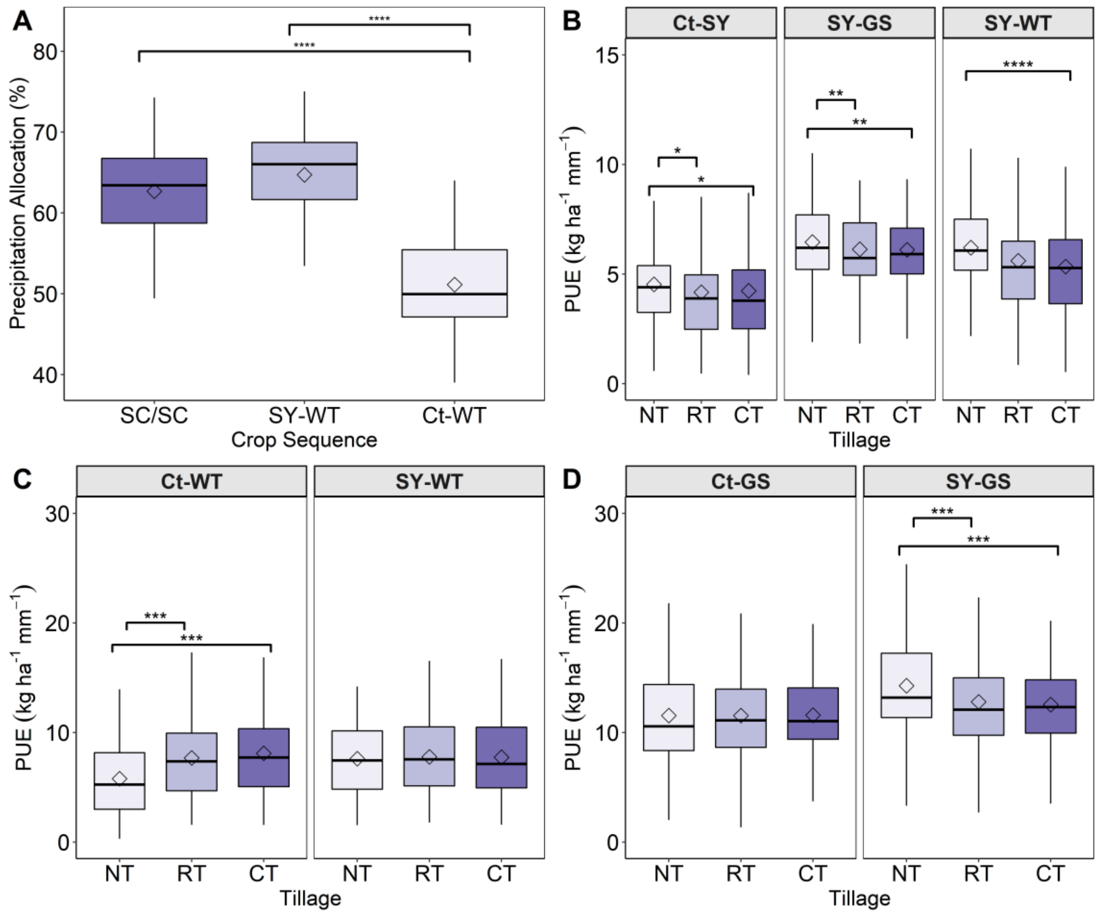

Fig. 2.4 Precipitation allocation (A) in three cropping systems (SC/SC = two consecutive summer crops; SY-WT = soybean-winter wheat rotation; and Ct-WT = continuous winter wheat) and precipitation use efficiency of soybean (B), winter wheat (C), and grain sorghum (D) in different cropping sequences (Ct-SY = continuous soybean; SY-GS = soybean-grain sorghum rotation; Ct-GS = continuous grain sorghum) under three tillage system (NT = no-tillage; RT = reduced tillage; CT = conventional tillage) in a 44-yr study (1974-2018) near Ashland Bottoms, KS. * significant at p = .05; ** significant at p = .01; *** significant at p = .001.

Soil organic carbon

Fig. 2.5 depicts SOC concentration in the three tillage systems in 1981, 2004, and 2018 at the 0-5 cm depth. The first SOC data were published 7 years after the experiment was established (Peterson, 1981). In this case, all tillage treatments had similar SOC, with a slight advantage for NT systems (15 g kg^{-1} for NT vs. 14.5 g kg^{-1} for RT and 14.0 g kg^{-1} for CT). Over the years, it was evident that NT practices enhanced SOC (+ 7 g kg^{-1}), followed by lower increase in RT (+ 2 g kg^{-1}) and no increase in CT. However, SOC did not vary at deeper depths (data not shown).

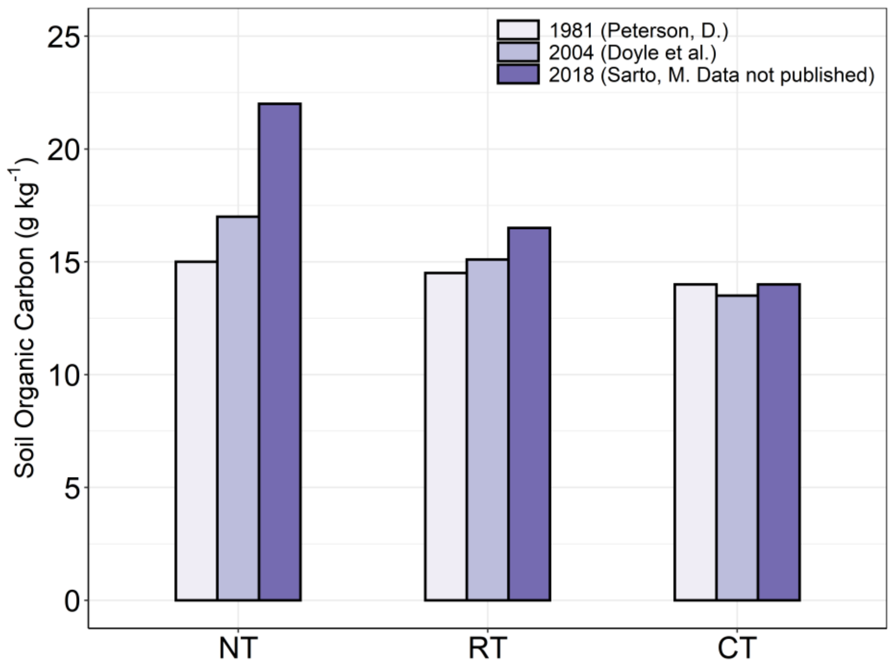

Fig. 2.5 Soil organic carbon at 0-5 cm depth as affected by tillage system (NT = no-tillage; RT = reduced tillage; CT = conventional tillage) in 1981, 2004, and 2018 retrieved from a 44-yr crop sequence and tillage system study (1974 – 2018) in Ashland Bottoms, KS.

Discussion

The benefits of rotational cropping compared to monocropping on crop yield and soil health are well reported in the literature (Edwards et al., 1988; Piorr, 2003; Leteinturier et al., 2006; Bowles et al., 2020; Liu et al., 2020), but few studies showed the benefits were consistent in the long-term (Congreves et al., 2015; Bowles et al., 2020; Renwick et al., 2021), which here were explored within a stability context. Our study revealed the yield benefits of rotational cropping for soybean and sorghum across an extended period, which was enhanced when associated with NT. Meanwhile, wheat showed little response to crop sequence or tillage, except for reduced yields when continuously cropped under NT. It was also evident that long-term NT increased SOC at the 0-5 cm depth with no variation at deeper soil layers, aligning with existing literature (Baker et al., 2007; Luo, Wang, and Sun, 2010; Lollato et al., 2012; Al-Kaisi et al., 2015). Finally, an original contribution of the current work is the cumulative analysis of yield for each crop over the 44-yr study period, which is informative as it highlights how minor differences in annual crop yields can accumulate and impact the long-term crop production at the farm level.

Winter wheat

The literature reports inconsistent and sometimes non-significant wheat yield response to rotation and tillage (Lund et al., 1993; Baumhardt & Jones, 2002; Lollato et al., 2019c; Schlegel et al., 2019a). Our study has original contributions to help clarify these relationships using a dataset with 44 continuous years of yield data. Grain yield of NT Ct-WT was lower and less stable than CT Ct-WT, but the CT benefit was absent when a soybean rotation was implemented. Thus, we suggest that the benefits of CT compared to NT for wheat are exclusive to mono-cropping, and crop rotations under NT bring benefits to offset the need for CT adoption. These findings are supported by long-term variety trial (Munaro et al., 2020) and grower-reported data (Lollato et al., 2019c) analyses in the region. The low yield and yield stability observed for NT Ct-WT may be potentially attributed to: (i) a decrease in soil pH due to the composition of wheat residue (Godsey et al., 2007; Schroder et al., 2011), (ii) greater weed infestation over time due to lack of herbicide rotation (Murphy & Lemerle, 2006; Young et al., 2013), (iii) increased incidence of soilborne (Smith, Kirkegaard, and Howe, 2004; Angus et al., 2015) and necrotrophic pathogens (near Hesston, 1992; Carignano et al., 2008) which can survive in wheat residue, and (iv) lack of benefits in soil water storage of NT as compared to CT when NT is adopted on continuous wheat (Patrignani et al., 2012).

Partial data from the current study published in Godsey et al. (2007) suggested that Ct-WT and NT plots had significantly lower pH than all other treatments, and consequently, aluminum toxicity may have limited wheat yield in this treatment (Lollato et al., 2013; 2019a). In a different experiment, Wright & Hons (2005) observed a higher C/N ratio and lower turnover rates in wheat residues than sorghum and soybean residues, which may have also decreased soil pH. From a weed control perspective, a major concern of downy brome (*Bromus tectorum*) infestation in NT Ct-WT was previously reported for the current study (Peterson and Roozeboom, 2007). Wheat yield losses are often correlated with greater weed density, especially grassy weeds (Pollard et al., 1982; Hume et al., 1991; Swanton et al., 1993; Sarani et al., 2014). In an 18-yr rotation study, Ruisi et al. (2015) observed that continuous wheat increased weed seedbank density and decreased weed diversity compared to wheat in rotation with other crops. Likewise, in a 10-yr tillage study, Campiglia et al. (2018) reported an increase in perennial weed population on minimal tillage compared to CT system in organic wheat under crop rotation. In both studies, weed control options for wheat became very limited when NT was not associated with crop rotation along with chemical weed control. In terms of crop rotation, Bushong et al., 2012 reported a ca. 12% greater yield of wheat grown succeeding a brassica crop rather than a wheat crop in the US Great Plains, with yield gains of similar magnitude due to crop rotation originating from other wheat growing regions (Arshad, Soon, and Azooz, 2002; Miller et al., 2003; Krupinsky et al., 2006; Kirkegaard et al., 2008; Kirkegaard and Ryan, 2014; Smiley et al., 2014). Beyond the better control of troublesome grass weed species (Bushong et al., 2012), the yield benefit was also attributed to a lesser incidence of some soilborne pathogens common in cereal monoculture systems (Smith et al., 2004; Angus et al., 2015).

Finally, while the benefits of NT to wheat in semi-arid regions are well reported due to its better soil water storage (Giller et al., 2015; Pittelkow et al., 2015), recent evidence suggests both NT and CT result in similar soil water storage at sowing when crop rotation is not adopted (Patrignani et al., 2012), offsetting some of these expected benefits. Our results showed that, when water is not a limitation (i.e., high-yielding years), the long-term benefits of NT were also offset, but the benefits of crop rotation still prevailed for wheat. Wheat was adaptable in both low- and high-yielding environments regardless crop sequence or tillage system, likely due to more conservative use of water throughout the crop's cycle (Lobet et al., 2014) and deep root systems (Manschadi et al., 2010; Sciarresi et al., 2019), which is essential in low-yielding environments. The adaptability in high-yielding environments demonstrates the crop's ability to explore environmental sources such as water. We note in passing that although the crop was adaptable to high seasonal weather variabilities like precipitation and temperature, management practices that maximize wheat yield under NT may differ from those under CT (Jaenisch et al., 2019; Munaro et al., 2020), suggesting that careful re-evaluation of management adoption is needed for growers transitioning from one tillage system to another.

Soybean

In rotation with another crop, soybean yields were significantly greater than monocropping across a wide range of environments in the current study. However, these benefits depend on environmental-yielding conditions because soybean yields after wheat were more adaptable to low-yielding environments, and soybean yields after sorghum were more adaptable to high-yielding environments. Similar results were found by Schlegel et al. (2019a) in a low-yielding semi-arid environment (455 mm annual precipitation), in which soybean yields were greater when following wheat rather than after another summer crop such as maize. The authors suggested that the benefit was due to greater off-season soil water accumulation at soybean planting, which likely explains our soybean adaptability results in low-yielding environments following wheat rather than sorghum.

Higher average yield and yield stability of soybean under rotation and NT are likely due to improvements in soil's physical, biological, and chemical properties (Doyle et al., 2004; McVay et al., 2006; Fabrizzi et al., 2007; Godsey et al., 2007; Yin et al., 2010). Studying SOC storage in the same plots reported in the current study, Fabrizzi et al. (2007) reported that Ct-SY had the lowest and most negative change in SOC, which reduced SOC over the years. The authors assigned this effect to soybean's residue composition, which has a low C:N ratio and higher turnover rates. Meanwhile, previous reports derived from the current study suggested that crop sequences that included wheat and sorghum had higher levels of SOC and water holding capacity, which can be explained by the greater above-ground biomass produced, higher C:N ratio, and more fibrous roots (hence influencing soil structure) of these two crops (McVay et al., 2006; Fabrizzi et al., 2007; Godsey et al., 2007). Additional reasons for the improved soybean yield in rotation may include the greater residue cover remaining after the cereal phase of the rotation, which can help control summer weeds due to shading (Crutchfield, Wicks, and Burnside, 1986; Liebl et al., 1992, Weisberger et al., 2019) and improve soil moisture retention (Schlegel et al., 2019b).

Grain sorghum

Sorghum grain yields were also enhanced under rotation with soybeans and decreased tillage intensity. When focusing on the tillage aspect, the greater yield for NT SY-GS than RT and CT was likely due to sorghum residue conservation, enhancing SOC over the years (Godsey et al., 2007). Although NT Ct-GS would also conserve a considerable amount of residue, low yield stability over the years observed for NT Ct-GS possibly explains the lower yields in Ct-GS compared to SY-GS rotation. The low yield stability for Ct-GS may be associated with weed pressure over the years resulted from lack of crop diversity (hence, lack of pesticide rotation) and lack of mechanical weed control, which are the two keys to weed herbicide resistance development (Swanton et al., 1993; Hicks et al., 2018). Shyam et al. (2020) reported for the first time the evolution of six-way herbicide resistance (ALS-, PS II-, HPPD-, PPO-, EPSPS-inhibitor herbicides, and synthetic auxins) in a single plant of Palmer amaranth (*Amaranthus palmeri*) in the Ct-GS plots in the current study, which confirms the lack of pesticide diversity and potential for development of herbicide resistance in weed populations in monoculture cropping.

Sorghum was more adaptable in low-yielding environments when planted continuously, possibly due to high residue produced, which contributes to better soil water conservation (Baumhardt, Johnson, and Schwartz, 2014), and deep roots, which enable the crop to reach deeper underground water (Assefa, Staggenborg, and Prasad, 2010). When rotating with soybean, sorghum was more adaptable in high-yielding environments if tillage was applied, probably due to the lack of soil water conservation, thus, requiring the crop to rely on in-season precipitation. However, when tillage was absent, NT SY-GS had wide adaptability in both environments and high stability and greater overall yield than all other treatments (Fig. 2.2B).

Precipitation allocation and precipitation use efficiency

Precipitation allocation intervals were proportional to the rainfall distribution for the region, which is mainly concentrated during the spring and summer (Rahmani et al., 2014). Thus, crop sequences with winter fallow periods such as Ct-GS, Ct-SY, SY-GS, and SY-WT had significantly greater PA than those with summer fallow periods. This suggests that, although crop sequence seems to be important when considering PA, the nature of the crop (e.g., summer crop *versus* winter crop) plays a more critical role in determining the PA as affected by the timing that the fallow period happens. In agreement, Patrignani et al. (2019) also observed greater PA in diversified cropping systems due to shifting fallow periods from summer to winter. The PUE values observed in this study differ from those previously published in the literature (Peterson et al., 1996; Peterson & Westfall, 2004; Patrignani et al., 2019) mainly because of the nature of the PUE calculation, which uses grain yield and rainfall data only. Thus, any difference in treatments, crop management, variety selection, and soil type will directly affect crop yield; different locations will also affect precipitation regime and, thus, PUE values. Expectedly, PUE was proportional to crop yield, as previously reported in the literature in which tillage or crop rotation affected PUE only when crop yield differed (Jones & Popham, 1997; Schlegel et al., 1999). The result also agrees with Schlegel et al. (1999), who suggested that NT sorghum had greater PUE than CT due to greater sorghum yields in the NT system.

Limitations of the current study

One limitation of this study relates to an issue commonly experienced in long-term agricultural studies, which is the modification of varieties and hybrids over time to accommodate modern genetics. While the change in varieties is common in long-term experiments (e.g., Raun et al., 1993; Lollato et al., 2019b), it creates a data structure in which variety/hybrid is nested within year, not allowing to clearly distinguish and eliminate the interaction effects of genetic × management. Because the majority (i.e., five out of six) of the adaptability indices pairwise comparisons that differed significantly year-to-year were related to wheat **(Supplement Figs. 1, 2, 3)**, we will focus on this crop for the purpose of this discussion. For example, the years of 1997 and 2013 were considered high-yielding environments for winter wheat because the annual mean yield for the crop in each of these years was in the upper third, regardless of management or genotype. Should the same wheat variety used in 2013 have been used in 1997, perhaps the yield in that environment would have been higher - provided that the assumption that modern varieties have greater yield potential is true. However, in the specific case of wheat, we note that the genetic gains in this region are lower than in other US regions (Lollato et al., 2020b) and more importantly, rates in yield gain have not maintained historical rates in the last 30-yr (Maeoka et al., 2020), perhaps justifying the few differences (five out of 60 comparisons for wheat, six out of 180 comparisons for the three crops) in adaptability among varieties tested in the different time periods (**Supplement Figs. 1, 2, 3)**.

Conclusions

Results from this 44-yr experiment highlight the long-term benefits of crop rotation and NT even in simpler crop rotations, such as those evaluated in the current study. Overall, our study showed that crops grown in rotation (cereal-legume) out-yielded continuous cropping in most instances, and the advantage was greater when associated with NT. In low-yielding years, crop rotation and NT showed significant advantages in crop yield over monocropping and when soil was tilled for soybean and sorghum. The two summer crops also showed greater grain yield,

yield stability, and crop adaptability to a wide range of environments in rotation rather than continuous cropping, regardless of the tillage system. Wheat grain yield slightly varied among treatments but showed the lowest yield under NT monocropping, evidenced by the lower yield stability, suggesting that NT is unsuitable for continuous wheat production. Although NT is environmentally friendly, the negative impact from continuous cropping appears to be greater when combined with NT than for other tillage systems. Our study demonstrated that cropping systems slightly affected PA in simplified crop sequences (one to two crops in 2-yr). Crop sequences and tillage system impacted PUE only when crop grain yield was affected by the system as well. From a practical perspective, our results suggested that i) farmers should consider using diversified cropping systems to enhance crop grain yield and long-term yield stability, ii) NT should be adopted in combination with appropriate crop sequences (i.e., crop rotation), and iii) the adaptability of a crop in a specific yielding environment (i.e., low- or high-yielding environment) depends on the crop sequence adopted based on the nature of the crop (i.e., summer crop *versus* cool season crops).

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Chapter 3 - Intensified nitrogen and cropping systems impact grain yield of winter wheat

Abstract

Intensified crop rotations can reduce winter wheat (*Triticum aestivum* L.) grain yield due to unfavorable sowing dates, potentially requiring tailored nitrogen (N) management. Here we explored the impacts of cropping system intensification and its interaction with N on the physiological determinants of winter wheat yield. A field experiment was conducted from 2020 to 2023 near Ashland Bottoms, Kansas, US, to evaluate sixteen combinations of three N management strategies (Standard, Progressive, and Green N) and ten cropping systems (Grain Only and Dual-Purpose systems with different levels of crop intensification). Standard and Progressive portrayed a baseline N-management and a system where all "4R" (right rate, time, source, and placement) were simultaneously improved, while Green N explored residual soil N from a previous legume summer crop. Intensifying N-management from Standard to Progressive only enhanced winter wheat yield in one out of four seasons but reduced N rates in two seasons without yield penalty. The split N-application impacted pre-anthesis N-uptake and, consequently, N nutrition index. Crop sequences and years created a 64-d range in wheat sowing dates, with a quadratic model explaining wheat relative yield as function of date. Crop sequences that allowed for optimum wheat sowing date had greater yield, partially due to lower temperatures during the critical period as compared to later sowings. Across all sources of variation, cropping systems and N practices that allowed for greater pre-anthesis N uptake and N nutrition index, and maturity biomass, plant N uptake, heads m^{-2}, and kernels m^{-2}, resulted in higher wheat yield.

Introduction

Kansas, the largest winter wheat (*Triticum aestivum* L.)-producing state in the U.S., accounts for ~22% of the country's wheat production (FAO, 2021). The dominant cropping systems in this state are centered around winter wheat. For example, the predominant systems in the western (semi-arid, Sciarresi et al., 2019) portion of the state are either wheat-fallow (14-mo fallow) or wheat-sorghum (*Sorghum bicolor* (L.) Moench)-fallow (11-mo fallow) (Nielsen et al., 2002). In the central (sub-humid, Sciarresi et al., 2019) portion of the state, about 50% of the area is grown to continuous winter wheat (3-mo fallow between crops) and the remaining consists of two/three-year rotations such as wheat-soybean (*Glycine max* (L.) Merrill) or wheat-corn (*Zea mays* L.)-soybean rotations (Jaenisch et al., 2021). Efforts to intensify cropping systems and reduce fallow periods in this region are warranted for improved rainfall capture and resource use-efficiency (Patrignani et al., 2019; Peterson & Westfall, 2004).

While cropping system intensification may benefit whole system efficiencies, it influences the sowing dates and, consequently, environmental variables (e.g., plant available water at sowing and temperature during critical periods of crop development) experienced during the winter wheat phase of the rotation. In water-limited environments, wheat has greater grain yield when sown after a fallow period or in rotations with fewer summer crops (Nielsen & Vigil, 2018; Schlegel et al., 2019). Water availability is one of the biggest challenges to intensifying wheat-based systems in those environments, as the length of the fallow period preceding the wheat crop can impact the amount of water available at sowing, which directly impacts yields (Tanaka & Aase, 1987; Lollato et al., 2016).

The timing of sowing modulates winter wheat yield potential in the U.S. central Great Plains (Munaro et al., 2020; Jaenisch et al., 2021). Winter wheat intended for forage or dual-purpose cultivation is typically sown earlier in the fall to maximize biomass production (Edwards et al., 2011), while winter wheat double-cropped after a summer crop tends to be sown later in the season, usually at the tail end of, or beyond, the optimum sowing window (Jaenisch et al., 2021; Munaro et al., 2020). While high fall biomass production is desired for dual-purpose wheat, grain yield may be compromised when wheat is sown too early in the fall due to excessive water consumption during the vegetative stages (Lollato et al., 2021; van Herwaarden et al., 1998). Conversely, a late sowing date can reduce wheat tillering potential in the fall and, consequently, heads m^{-2} (Spink et al., 2000), delay winter wheat's reproductive stages (Staggenborg et al., 2003), and reduce grain yield due to higher temperatures at critical period for yield determination (i.e., from onset of stem elongation until ~10 d post anthesis, when grain number is defined; Fischer, 1985), which decreases kernel numbers and shortens grain filling duration (Lollato et al., 2020; Cossani & Sadras, 2021).

Recent evidence suggests that wheat exposed to higher temperatures in the critical period for yield determination may warrant changes in nitrogen (N) management for improved N use efficiency (Cossani & Sadras, 2021; Lollato et al., 2021; Sadras et al., 2022). Current winter wheat yields are about 50% of their non-irrigated potential in Kansas and the US southern Great Plains (Lollato et al., 2017), and poor N management is among the leading causes of this large yield gap (De Oliveira Silva et al., 2020a; Jaenisch et al., 2021). Reducing yield gaps is essential for food security and requires crop intensification to use finite natural resources more efficiently (e.g., water, fertilizer, energy, and land) (Fischer et al., 2014). Still, nearly 50–70% of the N applied in the soil is lost (Hodge et al., 2000) and optimal N-management depends on yield-environment (Lollato et al., 2019). Since enhancing plant N uptake is key to maximize yields and N use efficiency (i.e., grain yield per unit N available) (de Oliveira Silva et al., 2020b), research evaluating N management within the scope of crop system intensification is warranted.

Strategies to optimize plant N uptake without increased amounts of fertilizer can include modifications to the method of fertilizer placement (e.g., broadcasting, injection, or streamer bars), application timing, and source, including N inhibitors with N fertilizer. Those methods are commonly known as the 4R framework (i.e., right rate, right time, right source, and right placement). While N rate is dependent on yield environment and cultivar (Giordano et al., 2024; Lollato et al., 2019), management of N timing (e.g., split N applications) can impact nitrogen use efficiency (Lollato et al., 2021) and N recovery (Souza et al., 2022). Regarding N source, a comprehensive meta-analysis and review encompassing studies conducted from the early 1970s to 2001, nitrapyrin – a nitrification inhibitor – enhanced crop yield by 7%, increased soil N retention by 28%, reduced nitrate leaching by 16%, and decreased greenhouse gas emissions by 51% (Wolt, 2004). More recent meta-analyses and reviews confirmed the potential for improved yield and environmental outcomes from technologies that reduce N losses (Abalos et al., 2014; Cantarella et al., 2018; Rose et al., 2018; Silva et al., 2017). However, intriguingly, approximately 25% of the time, nitrapyrin exhibited no discernible effect on agronomic or environmental N performance compared with N fertilization without nitrapyrin (Wolt, 2004). These results suggest that the benefits of nitrificator inhibitors are associated with prevailing weather conditions conducive to N losses like warm and wet environments, although, recent evidence suggested that volatilization from broadcast urea can also be significant even under cold conditions (Perin et al., 2020). These contrasting results suggest a need to further evaluate the value of this technology in the context of cropping system intensification.

Intensification of cropping systems is necessary to increase food production and improve precipitation use efficiency; however, it modifies the environment experienced by each crop in the rotation and can potentially impact crop N needs. Our objective was to explore the impacts of cropping system intensification on the wheat phase of the rotation and understand implications for N management using Kansas, US, as a case study.

Material and Methods

Site description

A no-till rainfed field experiment was initiated at the Kansas State University Ashland Bottoms Experiment Research Station (39°07'29.8" N, 96°38'06.4" W, altitude 325 m) near Manhattan, KS, USA in a silty clay loam (Wymore series, fine mesic Aquertic Argiudoll; United States Department of Agriculture (USDA), 2014) during the 2019-20 growing season and conducted for four winter wheat growing seasons until 2022-23. The experimental site had a sorghum-soybean-wheat rotation under conventional tillage (chisel plow, tandem disk, and field cultivator) before the onset of the experiment. Soil analyses at the beginning of the study (October 2019) revealed total C content of 1.47% (± 0.15), total N content of 0.17% (± 0.02), bulk density of 1.11 g cm-3 (± 0.15), pH 6.66 (± 0.54), and Mehlich-3 extractable P 14.32 ppm (± 5.68) at a depth of 0-15 cm.

Weather data and crop simulation

Weather data was sourced from a Kansas Mesonet (Patrignani et al., 2020) weather station located 166 m from the experimental site. The historical records spanning 33 years indicate an average annual rainfall of 876 mm, an average annual temperature of 12.4 °C, and a frost-free period of 179 days.

We created a water stress index variable for each evaluated treatment using crop simulation modeling. Here, we simulated non-irrigated wheat yield potential for each treatment during the four consecutive harvested years (2020-2023) using ‘Simple Simulation Model’ (SSM) (Soltani & Sinclair, 2012), which is a mechanistic crop model that simulates daily wheat growth and development with no limitations caused by diseases, insects, weeds, or nutrient deficiencies. Its operation is based on daily time steps and requires input of soil data (water content at saturation, field capacity, and wilting point; plant available water (PAW) at sowing, drainage factor, bulk density, etc.), daily weather data for solar radiation, minimum and maximum air temperatures, and precipitation, and crop management data (sowing day of year and plant density). Model parameters for phenology and wheat grain yield potential were calibrated using data from seven dryland site-years and four irrigated site-years in the US southern Great Plains (Lollato & Edwards, 2015) for the wheat cultivar ‘Iba’ (Edwards, 2013) and the validation of the model performance occurred using data from 43 site-years in Oklahoma and Kansas (Supplement Fig. B1) as detailed in Lollato et al. (2017). Further, we validated the simulated phenology of this previously calibrated crop model against dates of jointing (Zadoks 32), anthesis (Zadoks 65), grain soft dough (Zadoks 85) and physiological maturity (Zadoks 92) measured in the current study to ensure that the modeled stressors related to the phenology experienced in the field. This exercised resulted in a RMSE of 16.5 days (7.38%) (Supplement Fig. B1), which is acceptable for crop modeling purposes.

Output from the SSM-Wheat modeling exercise used in our weather characterization analyses were actual and potential crop evapotranspiration, in-season precipitation, temperature during the periods of jointing to anthesis and from anthesis to physiological maturity. We also estimated the critical period for grain yield determination as starting at ca. 300°C thermal units accumulated before anthesis and lasting until about 100°C after anthesis (Couëdel et al., 2021; Sadras et al., 2022). We computed the Water Stress Index as [1 – (cumulative transpiration/potential transpiration)] to assess the degree of water stress experienced by each treatment (e.g., Couedel et al., 2021). Values closer to 0 indicate minimal water stress and values closer to 1 signify higher levels of water stress.

Experimental design and treatment description

The field experiment was established as a randomized complete block design with four replications, with treatments arranged in an incomplete factorial treatment structure. The treatments consisted of sixteen distinct combinations of ten cropping systems (refer to Fig. 3.1) and three strategies for N-management, namely ‘Standard’, ‘Progressive’, and ‘Green N’.

Cropping systems

The Baseline system consisted of continuous winter wheat under Standard N-management (Fig. 3.1). In the Dual-purpose summer forage system, summer-fallow was replaced with a summer forage in two out of three summers, and N-management was intensified to Progressive. Cropping systems were then organized into two primary categories based on their intended purposes: i) grain-only production and ii) dual-purpose (grain and forage) production. Varying levels of intensity were implemented within each category – Less intensive, Semi-intensive, Intensive, and More intensive for grain-only; and Semi-intensive and Intensive for dual-purpose (Fig. 1). Intensity levels were determined by the i) the total amount of crops harvested (ranging from 5 to 7 crops in four years) and ii) frequency (zero to three) and allocation (winter or summer) of fallow periods. Systems with the same numbers of crops harvested, but with winter fallow instead of summer fallow were considered less intense (Patrignani et al., 2019). Specifically, higher intensity systems entailed more frequent crop harvests and fewer fallow periods, whereas lower intensity systems involved less frequent harvests and more fallow periods.

N-management

Standard and Progressive N treatments were designed to portray a baseline N-management common to most growers in Kansas, versus a system where all "4R" (right rate, right time, right source, and right placement) were simultaneously improved (Supplement Table A1). Thus, these treatments differed in the application source (absence vs. presence of urease and nitrification inhibitors), timing (single vs. split N-application), placement (broadcast vs. streamed), and rate (flat vs. adjustable rate). In the Standard treatment, a single flat rate of 90 kg ha^{-1} of UAN (Urea Ammonium Nitrate; 28-0-0 of N–P2O5–K2O) was broadcast at spring green-up (Zadoks growth stage 30). Conversely, the Progressive treatment had a split N application with the first application timing at beginning of spring green up (Zadoks 30) with a flat rate of 45 kg ha^{-1}, and a second application around jointing (Zadoks 32) with adjusted N-rate determined by in-season N recommendation simulated using an integrated modeling framework. This framework was developed based on a combination of biophysical and economic models. The Environmental Policy Integrated Climate model (EPIC) was utilized to forecast crop yields under 18 different N rates, ranging from 0-240 kg N ha^{-1}, using Subseasonal Experiment (Subx) daily weather forecasts (Pegion et al., 2019). The Optimal Autoregressive Moving Average (ARMA) model (Chambers and Serra, 2019) was also applied to predict winter wheat grain prices. Both forecasted yields and price predictions were used as inputs in the Constant Absolute Risk Averse (CARA) expected utility model (Acs et al., 2009) and predicted N recommendations under different risk categories, such as risk averse, risk- neutral and tolerant categories. For this study, N recommendations under the risk-neutral category were used and resulted in recommendations of the same rate as the Standard in 2020, a net N savings of 10 kg N ha^{-1} in both 2021 and 2022, and an extra 10 kg N ha^{-1} in 2023. For both N applications in the Progressive treatment, a mixture of urease + nitrification inhibitor (pronitridine, 2.50 kg a.i. ha^{-1}) and a nitrification inhibitor (0.15% NBPT wt/wt) was combined with UAN and applied using streamer nozzles (SJ3-10-VP, TeeJet Technologies Spraying Systems Co., Glendale Heights, IL 60139) rather than broadcast. The Green N treatment was designed to build up soil N levels. This involved the deliberate inclusion of high N-fixing legume crops (i.e., tepary, Phaseolus acutifolius A. Gray; moth, Vigna aconitifolia (Jacq.) Marechal; forage soybean; or alfalfa, *Medicago sativa* L.) during each summer, aimed at creating a residual N pool for subsequent winter crops. Notably, the Green N plots did not receive external N application, relying solely on the N-fixing capabilities of the integrated legumes.

Study establishment and harvest

The winter wheat variety Zenda was sown using a 9-row Great Plains 506 no-till drill on 185.4 m2 plots (12.2 m wide × 15.2 m long) with a 0.19 m row spacing. Sowing date and seeding rate varied across treatments as a consequence of different crop sequences (refer to Section 2.3) and the intended crop purpose (i.e., forage only, dual-purpose, or grain only). Dual-purpose winter wheat had an early sowing date (mid-September) and greater seeding rate (132 kg seed ha^{-1}) for greater biomass accumulation for grazing during the fall (Edwards et al., 2011; Lollato et al., 2019). Grain-only winter wheat was sown either at optimum or late sowing date, depending on cropping system. Seeding rates followed local recommendations and varied with sowing date, from 100 to 132 kg seed ha^{-1} for optimum and late sowing, respectively (Staggenborg et al., 2003). Seeds were treated with thiamethoxam (0.016 kg a.i 45 kg^{-1} seed), sedaxane (0.0012 kg a.i 45 kg^{-1} seed), difenoconazole (0.0055 kg a.i 45 kg^{-1} seed), mefenoxam (0.0014 kg a.i. 45 kg^{-1} seed) to avoid problems associated with early season diseases and pests. Diammonium phosphate (DAP 18-46-0) was uniformly applied to all plots at a rate of 56 kg ha^{-1} at sowing in-furrow as a starter fertilizer. Spring herbicide application consisted of recommended commercial label rates mixtures of thifensuifuron-methyl, MCPA, and nonionic surfactant at Zadoks 30 growth stage. No significant occurrences of disease or insects were noted during the study, and neither in-season fungicides nor insecticides were applied.

Grain yield was determined by combine harvesting 28 m2 of the experimental unit using a self-propelled Massey Ferguson XP8 small plot combine and weighed by a harvest master (Juniper Systems, Logan, UT). The harvest master system also measured grain moisture and test weight. Grass weed infestation (*Hordeum pusillum* and *Bromus tectorum* L.) on a few late-sown plots during the last growing season (2022-2023) required hand-harvest of all plots for uniform grain yield data collection on an area of 2 m2. A combination of burndown herbicides and manual weeding was necessary for weed control during the fallow periods. For cover crop, forage, and summer crops agronomic management information, please see Supplement Section 1 and Table A2.

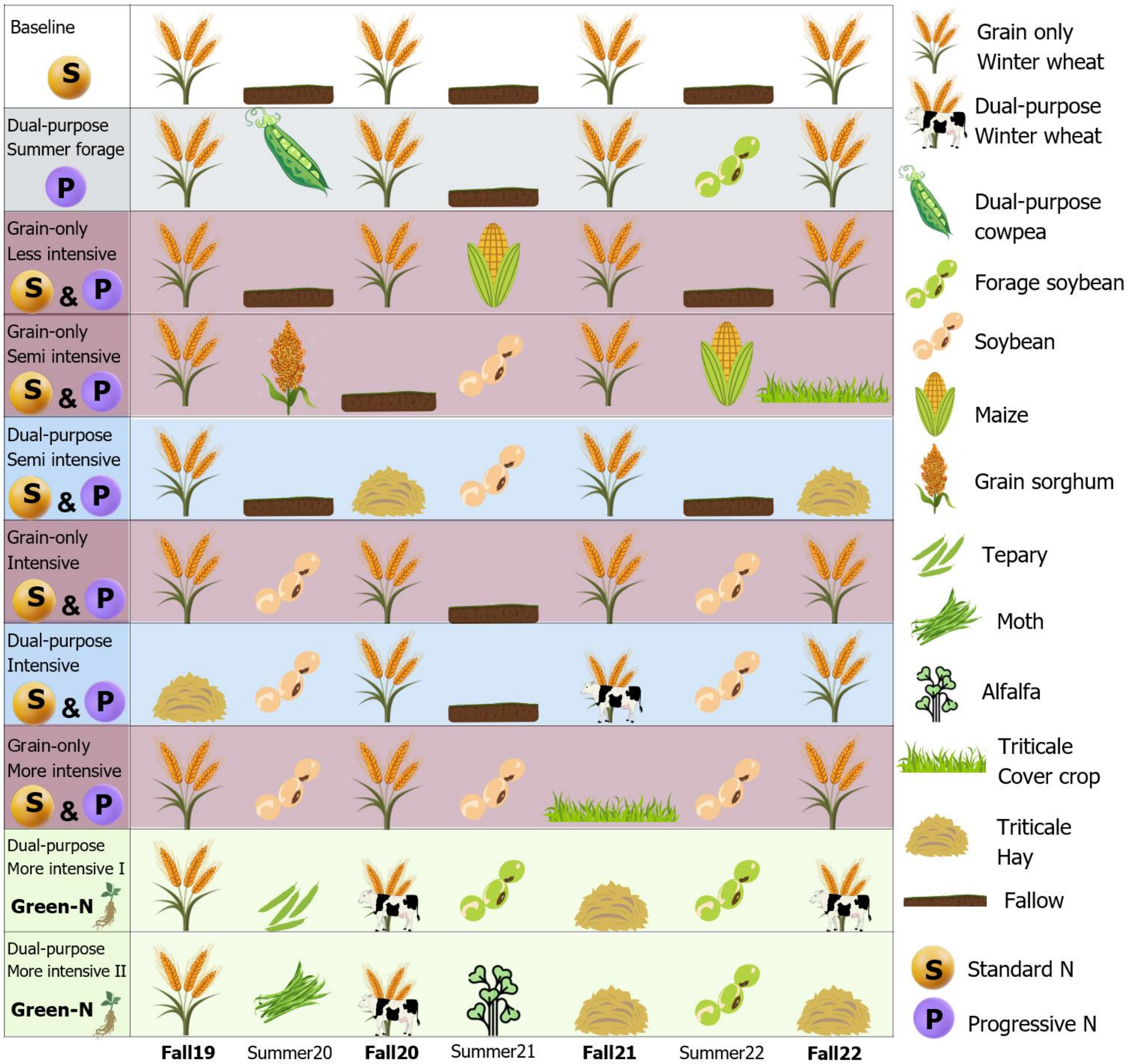

Fig. 3.1 Ten wheat-based cropping systems (2019-2023) near Ashland Bottoms, KS, varying in intensity and nitrogen management: Standard (S), Progressive (P), and Green N (refer to Table A1). Half of the treatments were designed for grain-only production (brown shade) and half for dual-purpose (grain and forage - light blue shade).

Measurements and calculations

Winter wheat grain yield, yield components (e.g., stand count, shoot biomass at maturity, harvest index, heads m^{-2}, kernels $head^{-1}$, kernels m^{-2}, and thousand kernel weight), and plant N dynamics (e.g., whole plant N-uptake, grain N-uptake, grain protein content, pre-anthesis N-uptake, and post-anthesis N-uptake) were measured. Stand count was measured one to four weeks after sowing in a linear meter within the middle rows at two different locations within each experimental unit. Yield components were determined from biomass samples collected at maturity and reported on a dry weight basis. Aboveground biomass was harvested from one linear meter of a middle plot row per experimental unit at key growth stages, including the beginning of stem elongation (Zadoks 31), anthesis (Zadoks 59), the soft dough stage of grain development (Zadoks 85), and physiological maturity (Zadoks 93).

After drying for 48 hours at 60 °C, the plants were weighed and then partitioned into head and stover for head count and weight measure. Heads were separated for grain and chaff analysis using a Wheat Head Thresher (Precision Machine Co., Lincoln, NE, US). All plant parts (stover, chaff, and grain) were ground to pass a 2 mm sieve and sent to the laboratory for nutrient concentration analysis via combustion using the LECO TruSpec CN and S analyzer (LECO). Plant N-uptake was estimated as the product of N concentration and biomass on a dry weight basis at each sampled stage.

For each treatment, the efficiency of N dynamics within the plant were determined by calculating the N harvest index (ratio of grain N-uptake per whole plant N-uptake) and internal efficiency (ratio of grain yield per whole plant N-uptake). The status of N in the plant (i.e., low/stress, optimum, or high/luxury concentration) at a given biomass was determined by calculating the N nutrition index of each treatment. N nutrition index was calculated as the measured shoot N concentration at anthesis divided by the critical N concentration for the associated biomass level. The critical N concentration for the associated biomass level was described by Justes et al. (1994) and follows the equation: [Nc] = 5.35 × biomass –0.442.

Grain samples were retrieved from the combine and cleaned using an air-blast seed cleaner (Alma, Co SABSCIC, Nevada, IA) to remove foreign material. Grain protein concentration (g kg^{-1}) was determined using near-infrared reflectance spectroscopy with a Perten DA 7200, and together with grain yield is reported on a 135 g kg^{-1} water basis. When analyzing the data across years, relative grain yield was calculated as the yield of each experimental unit divided by the annual maximum yield.

Statistical analysis

All statistical analyses were conducted using R programming language (R Core Team, 2023) and significant effects were set at $\alpha = 0.05$. A two-way analysis of variance (ANOVA) Type III was performed to examine the grain yield, considering treatments and years as fixed effects, and replication as a random effect nested within year. Due to a significant interaction between treatment and year, further analyses were done by year.

Considering the incomplete factorial structure of the experiment, we utilized orthogonal contrasts to compare treatment levels within years. Bonferroni adjustment was applied to control the overall Type I error rate resulting from multiple comparisons made annually. Due to variations in treatments across different growing seasons—such as the inclusion of triticale as a cover crop or hay during winter—certain comparisons were not applicable every year.

Consequently, orthogonal contrasts were strategically planned on a yearly basis (detailed in Supplement Table A3), focusing on comparisons that held agronomic significance for that specific year. For each orthogonal contrast identified as a significant factor impacting grain yield within each year, we further evaluated other independent variables (e.g., yield components and N-dynamics variables, as described in Section 2.4) as impacted by the significant factors driving yield to understand the physiological changes to the wheat crop explaining the yield response. This analysis entailed first performing t-tests to compare whether the means of each independent variable were different between groups and, when they were significantly different, employing linear models to identify significant relationships between the given variable and grain yield. Only N-management was compared in the first year since it was the study establishment year and the effect of crop sequences had not yet taken place.

For a final, global analyses of the impact of the combination of years, cropping systems, and N strategies on wheat grain yield, we utilized the mean deviation generated by each specific treatment within a given year, aiming to isolate the treatment effects on the considered traits. This involved a straightforward subtraction of each treatment's value from the annual mean of all treatments within that year. The adoption of this approach standardized significant variations in absolute values arising from diverse experimental conditions and isolated treatment effects. A linear model was used to assess the degree of linear relation between each normalized independent variable (i.e., yield components and N dynamics) and normalized grain yield.

Results

Weather

During growing season, precipitation ranged from 446 to 563 mm and ETo ranged from 645 to 707 mm (Fig. 3.2). Different sowing dates across the years resulted in a range of 132 to 144 days pre-anthesis, which led to temperatures during the critical period for yield determination ranging from 14 to 19.3°C. The 2019-20 growing season had the closest water supply to crop water demand totals, and the 2022-23 was the driest season overall. The combination of treatments and years resulted in 22% of the evaluated treatment-years exposed to hot-dry weather conditions, 33% to cool-dry weather conditions, 20% to hot-wet weather conditions, and 25% to cool-wet growing conditions (Fig. 3.3).

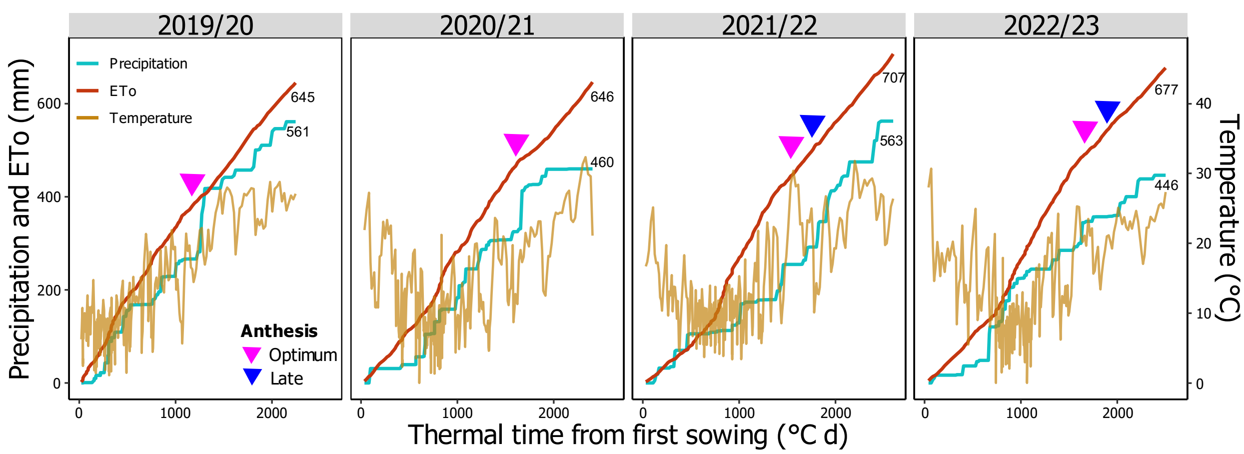

Fig. 3.2 Weather conditions experienced during the winter wheat-growing season for four consecutive years near Ashland Bottoms, KS. Lines show cumulative reference evapotranspiration (ETo), precipitation, and average daily temperature. Inset values show cumulative ETo and precipitation. Triangles display the occurrence of anthesis (Zadoks 59) based on different sowing periods (Optimum or Late).

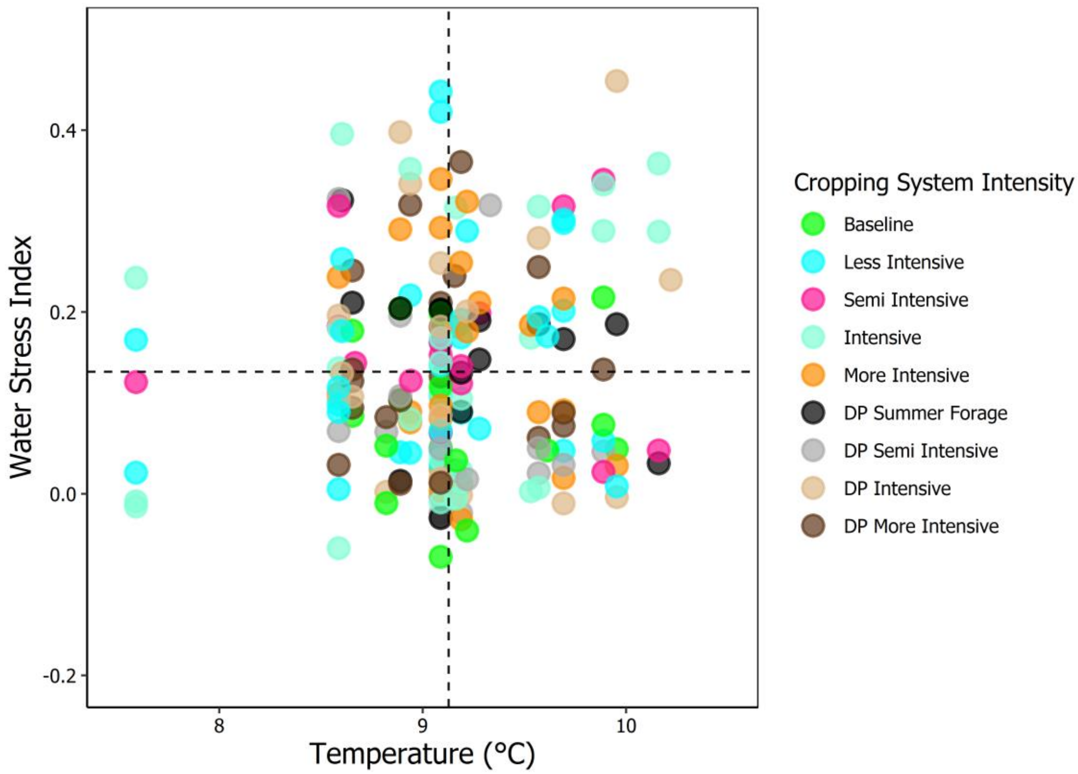

Fig. 3.3 Water stress index and temperature experienced by different system's intensity during the winter wheat-growing season across four growing seasons near Ashland Bottoms, KS. Abbreviation: DP = Dual-purpose.

Treatment effects on grain yield of winter wheat

Wheat grain yield ranged from 0.6 to 4.5 Mg ha^{-1} across all treatment-years, with significant effect of treatment in each year (Table 3.1). Average grain yield across all treatments were 3.5, 3.1, 2.4, and 2.3 Mg ha^{-1}, respectively, from 2020 until 2023. The range in grain yield within each year was 3.6 to 4.9, 1.6 to 4.6, 0.6 to 3.3, and 1.0 to 3.5 Mg ha^{-1}. Ten sets of orthogonal contrasts evaluating the differences in grain yield were significant (Table 3.2). Values of grain yield and independent variables (i.e., yield components, N-dynamics, and indexes) of each contrast are depicted on Supplement Figs. S2 – S11. Hereafter, we exclusively report contrasts that significantly differed in grain yield (Table 3.2) and the independent variables that were significantly different for each contrast (Supplement Figs. S2 – S11).

Table 3.1 Annual winter wheat grain yield under nine cropping systems and three N-management during four growing seasons in Ashland Bottoms, KS.

System's Purpose	System's Intensity	Growing season > N-management	2019/20	2020/21	2021/22	2022/23
			------------------- Yield[1] (Mg ha^{-1})			-------------------
Grain Only	**Baseline**	Standard	3.3 ± 0.08	4.5 ± 0.17	2.6 ± 0.13	2.7 ± 0.20
	Less Intensive	Standard	3.4 ± 0.06	4.1 ± 0.06	1.3 ± 0.25	2.8 ± 0.30
		Progressive	3.6 ± 0.13	3.7 ± 0.22	1.06 ± 0.24	2.9 ± 0.21
	Semi Intensive	Standard	3.4 ± 0.12	.[2]	3.4 ± 0.12	.
		Progressive	3.5 ± 0.10	.	2.8 ± 0.10	.
	Intensive	Standard	3.3 ± 0.09	2.9 ± 0.16	2.8 ± 0.16	1.7 ± 0.13
		Progressive	3.3 ± 0.05	2.8 ± 0.04	3 ± 0.13	1.8 ± 0.24
	More Intensive	Standard	3.6 ± 0.15	3.3 ± 0.11	.	2.6 ± 0.09
		Progressive	3.7 ± 0.03	2.7 ± 0.08	.	2.8 ± 0.12
Dual-Purpose	**Summer Forage**	Progressive	3.6 ± 0.05	2.5 ± 0.13	2.7 ± 0.14	2.1 ± 0.22
	Semi Intensive	Standard	3.2 ± 0.05	.	3.0 ± 0.15	.
		Progressive	3.4 ± 0.20	.	2.7 ± 0.13	.
	Intensive	Standard	.	3.9 ± 0.13	2.2 ± 0.21	2.5 ± 0.08
		Progressive	.	3.8 ± 0.07	2.3 ± 0.06	2.2 ± 0.13
	More Intensive	Green N I	3.4 ± 0.08	1.7 ± 0.12	.	1.13 ± 0.06
		Green N II	3.4 ± 0.06	1.6 ± 0.17	.	.

[1] ± represents standard error.
[2] represents treatments from which grain yield was not harvested in a particular year.

Table 3.2 Orthogonal contrast for selected treatments evaluating the effects of nitrogen management and crop sequence on grain yield of winter wheat during four growing seasons near Ashland Bottoms, KS. The "-" denote an orthogonal contrast that was not possible in a given year due to the phase of the experiment.

Orthogonal contrast[1] **Growing season >**	**2019/20**	**2020/21**	**2021/22**	**2022/23**
	--------------------- *p*-value			---------------------
Nitrogen levels				
Standard vs. Progressive	.875	.388	.965	.009*
Nitrogen vs. Green N	.786	.029*	-	.129
Crop sequence levels				
System's purpose				
Grain-only vs. Dual-purpose	-	<.0001**	.264	-
Baseline vs. Dual-purpose summer forage	-	.0001*	.112	.954
Intensive grain-only vs. Intensive dual-purpose	-	-	-	.021*
System's intensity				
Intensive vs. More intensive [Grain-only]	-	-	-	.001*
Semi intensive vs. Intensive [Dual-purpose]	-	-	.247	-
Nitrogen *x* Crop sequence				
Baseline vs. All [Standard]	-	<.0001**	.188	.899
Standard vs. Progressive [Grain-only]	-	.813	.483	.928
Standard vs. Progressive [Dual-purpose]	-	.067	.352	.071
Sowing date				
Optimum vs. Late	-	<.001**	<.001**	.0001*

Sowing date

Across years, sowing dates ranged from day of year 262 to 326 (September 19 to November 22). Optimum sowing date was estimated as 297 ± 5 day of the year (October 27th). Treatments sown close to the optimum date had significantly greater yields than later sowing dates (Fig. 3.4A). Later sowing dates also led to higher temperatures at the critical period for yield determination across years, with a slope of 0.24 ± 0.04 Mg ha^{-1} $°C^{-1}$ (Fig. 3.4B).

Sowing dates impacted grain yield significantly at all three years when different sowing dates were evaluated (i.e., except for the trial establishment year; Table 3.2). In the second year, optimum sowing date resulted in greater grain yield than late (3.6 vs. 2.7 Mg ha^{-1}). Physiological mechanisms behind these responses included greater biomass, pre-anthesis N-uptake, and N nutrition index (Fig. 3.4 C-E) at optimum sowing in the second year. In the third year, greater grain yield for optimum sowing date than late (2.8 vs. 1.9 Mg ha^{-1}, respectively) likely due to greater N harvest index and internal efficiency, that were positively related to grain yield (Fig. 3.4 F-G). Additionally, water stress index was negatively correlated to grain yield and was lower for optimum sowing dates than later (Fig. 3.4H). In the fourth year, optimum sowing date was also greater than late (2.6 vs. 2.0 Mg ha^{-1}, respectively); however, there was no statistical difference in yield components or N dynamics.

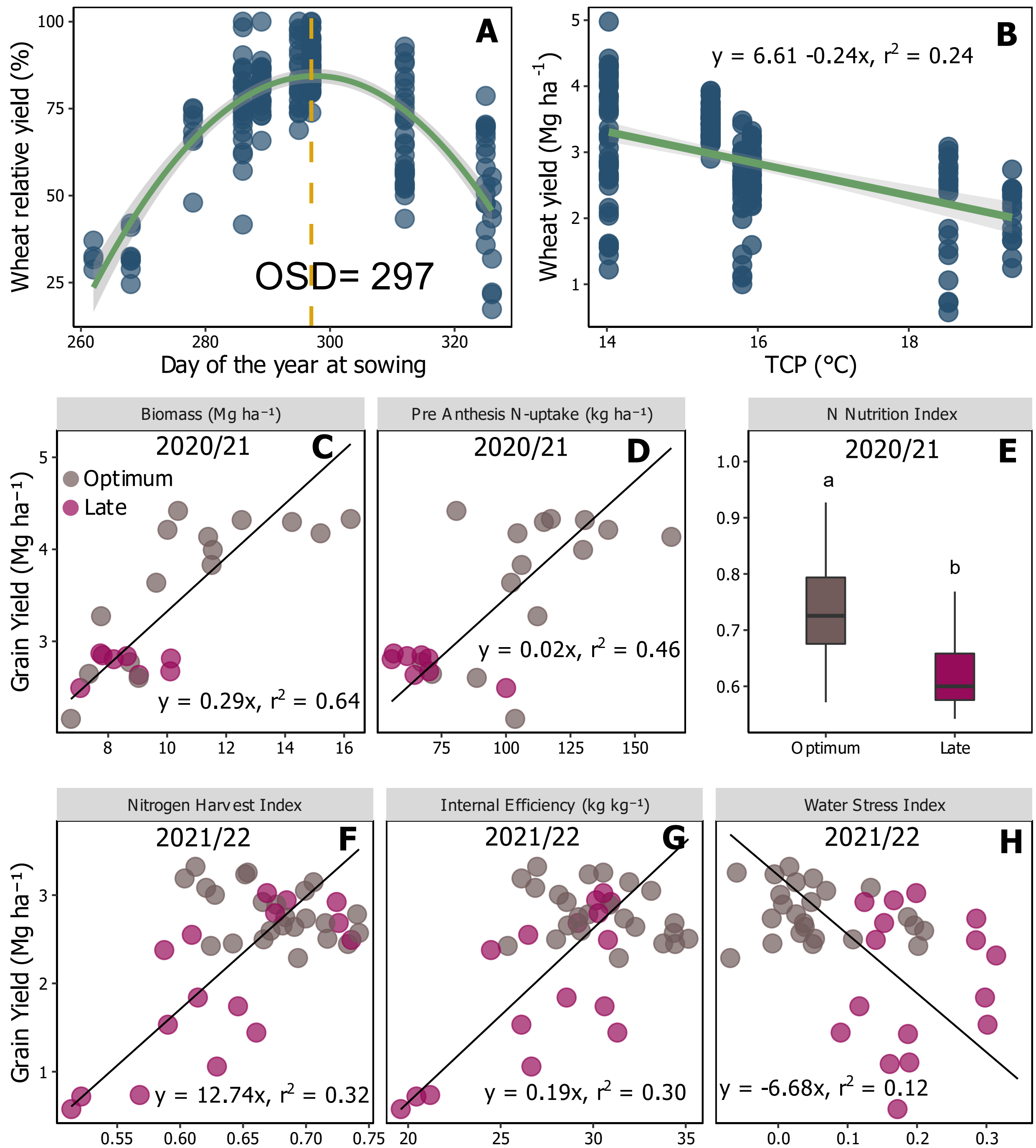

Fig. 3.4 Quadratic relationship between wheat relative yield and day of the year at sowing (A); linear relationship of wheat yield and mean temperature at critical period (TCP) (B); relationship between grain yield and biomass (C) and pre-anthesis N-uptake (D), and N nutrition index (E) of winter wheat for Optimum and Late sowing dates during 2020/21; and relationship between winter wheat grain yield and N harvest index, internal efficiency, and water stress index (F-H) for optimum and late sowing dates. Optimum sowing date (OSD) is estimated at day 297 ± 5 (mid-Oct).

Nitrogen levels

Standard and Progressive N management only led to significant differences in grain yield during the final year of the study, with Progressive showing a greater grain yield than Standard (2.5 vs. 2.3 Mg ha^{-1}) (Table 3.2). There was no statistical difference in yield components between the two N managements (Supplement Fig. B3), but physiological mechanisms that led to higher yields with Progressive compared to Standard included greater whole plant N-uptake (ca. 109 kg ha^{-1} vs. 90 kg ha^{-1}) and grain N-uptake (ca. 74 vs. 61 kg ha^{-1}, respectively) (Fig. 3.5A,B). Although Standard showed greater internal efficiency (measured as the unit of grain produced per unit of N uptake) compared to Progressive (30.5 vs. 28 kg kg^{-1}, Fig. 3.5C), the overall whole plant N-uptake was lower.

In the second year of the study, treatments with applied N fertilizer (both Standard and Progressive) had higher grain yields than treatments with no external N application (i.e., Green N) (3.4 vs. 1.6 Mg ha^{-1}, respectively). All yield components were greater for wheat crops receiving N fertilizers compared to Green N (Supplement Fig. B4), except stand count, which was similar across treatments. Increased yield as function of N fertilizer resulted from greater biomass, whole plant N-uptake, N nutrition index, grain N-uptake, and pre-anthesis N-uptake, alongside a lower water stress index (Fig. 3.5 D-I).

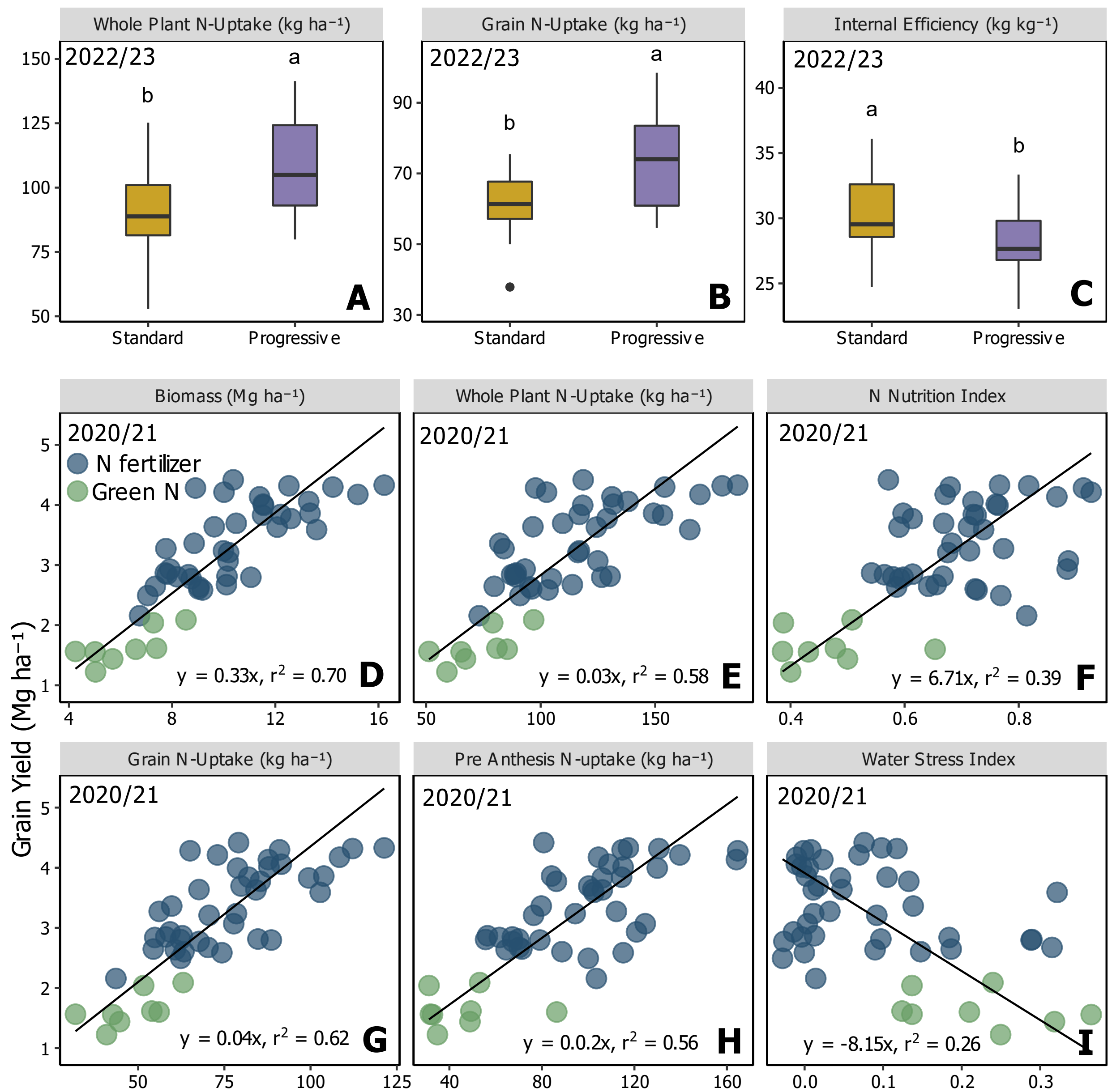

Fig. 3.5 Nitrogen dynamics of winter wheat under Standard and Progressive N-management (A – C); and the relationship between winter wheat grain yield with applied (Standard and Progressive) and non-applied N fertilizer (i.e., Green N, D – I) during 2022/23 and 2020/21 growing seasons, respectively, in Ashland Bottoms, KS.

Crop sequence levels

System's purpose

In the second year, when comparing the yield of grain only wheat grown after a full season soybean - which was planted after triticale for hay (i.e., "dual-purpose system"), with the yield of grain only wheat grown after a double crop soybean planted after a full season wheat crop (i.e., "grain only system"), the dual-purpose system had greater yield than the grain-only system (3.9 vs. 2.9 Mg ha^{-1}, respectively). Here, grain only wheat in the grain-only systems followed a double-cropped soybean, which resulted in a considerably later sowing date. Among the physiological mechanisms in each system, internal N efficiency was greater in dual-purpose systems (Fig. 3.6A), although the most likely cause for the lower yield in grain-only systems was the greater water stress index caused by the more intensified, late sown system (Fig. 3.6 B). Additionally, dual-purpose wheat produced greater biomass and had higher pre-anthesis and grain N-uptake – components that were all positively related to grain yield (Fig. 3.6 C-D, G-H). Dual-purpose systems also had greater head number (880 vs. 725 m^{-2}, respectively), kernel number (15,432 vs. 12,049 m^{-2}), and thousand kernel weight (27 vs. 26 g m^{-2}, respectively) than late-sown grain-only systems.

Under the Intensive N management system, dual-purpose wheat had greater grain yield than late-sown grain-only wheat (2.4 vs. 1.8 Mg ha^{-1}) in the fourth year (Table 3.2), which was mainly driven by greater kernel number (13,328 vs. 9,190 m^{-2}), shoot biomass, grain N-uptake, and nitrogen harvest index (Fig. 3.6 I-K).

While late-sown wheat underperformed compared to dual-purpose, grain yield of the baseline continuous wheat crop was greater than the dual-purpose wheat grown after a summer forage in the second year (Table 3.2, 4.3 vs. 2.5 Mg ha^{-1}). This yield difference was mostly driven by greater kernel number (17,015 vs. 10,066 kernels m^{-2}), whole plant N-uptake, and grain N-uptake (Fig. 3.6 E-F).

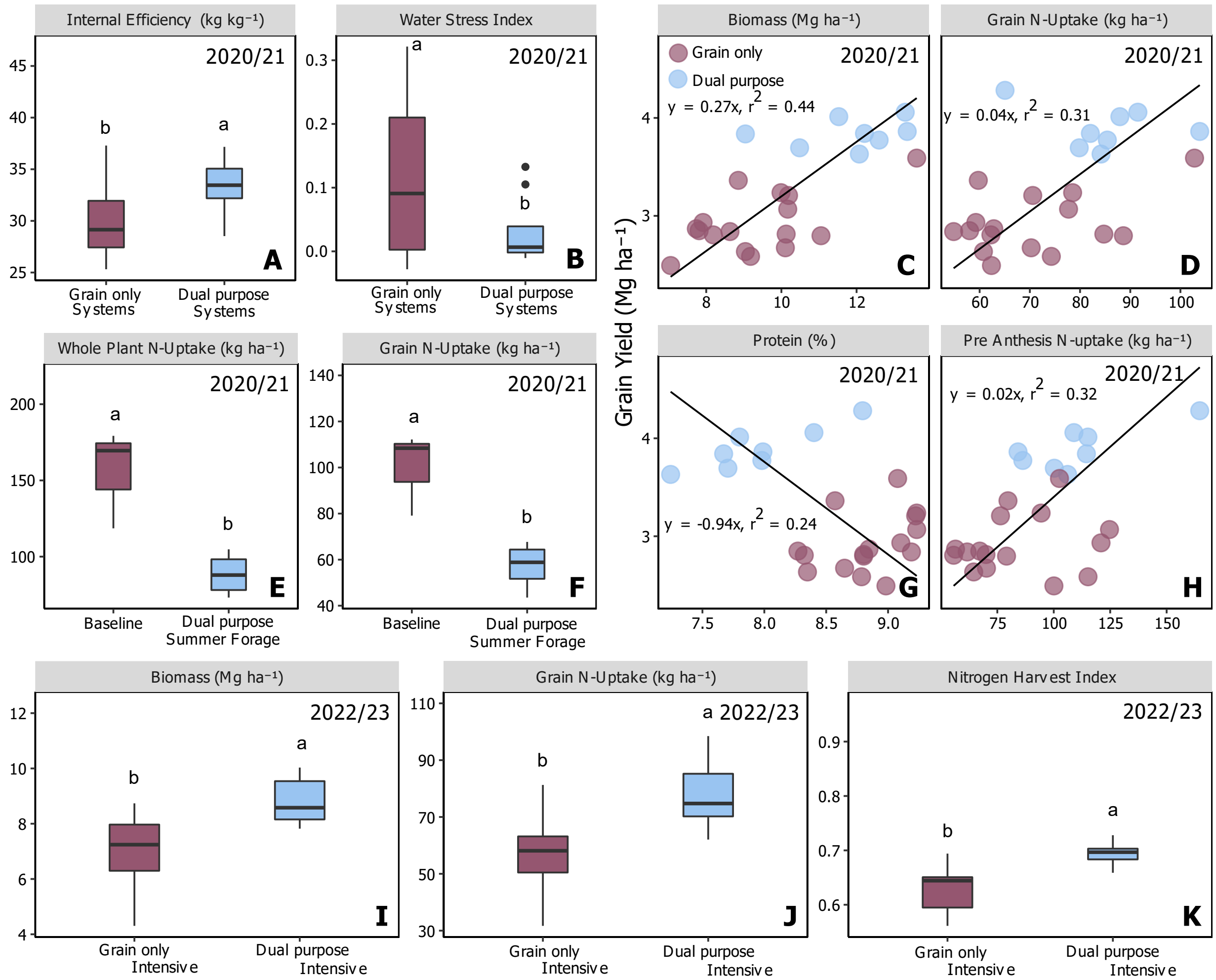

Fig. 3.6 Grain-only (red) versus dual-purpose (blue) systems. Panels A and B display internal efficiency (i.e., unit of grain yield per unit of whole plant nitrogen uptake) and water stress index during 2020/21 growing season. Panels C, D, D, and H show the significant ($\alpha = 0.05$) relationship between grain yield and biomass, grain N-uptake, protein, and pre-anthesis N-uptake, respectively, of grain-only and dual-purpose systems during 2020/21 growing season. Panels E and F show whole plant and grain N-uptake, respectively, of Baseline system (i.e., continuous winter wheat-summer fallow system for grain-only) and dual-purpose summer forage (i.e., grain only winter wheat - summer forage system). Panels I-K display biomass, grain N-uptake, and nitrogen harvest index (i.e., unit of grain N-uptake per unit of whole plant N-uptake) of grain-only and dual-purpose systems under intensive crop sequence (refer to Fig. 3.1).

System's intensity

Within grain-only systems, grain yield of More intensive was greater than Intensive system (2.7 vs. 1.8 Mg ha^{-1}, respectively) in the fourth year (Table 3.2). In that year, wheat in the More intensive system was sown following a full-season soybean, while wheat in the Intensive system was sown after a double-cropped soybean – which resulted in a later sowing date. More intensive system had greater kernels per head (19 vs. 16, respectively), N harvest index (Fig. 3.7A), and pre-anthesis N-uptake (Fig. 3.7B). Within dual-purpose systems, there was no grain yield difference between Semi-intensive and Intensive systems in the third year.

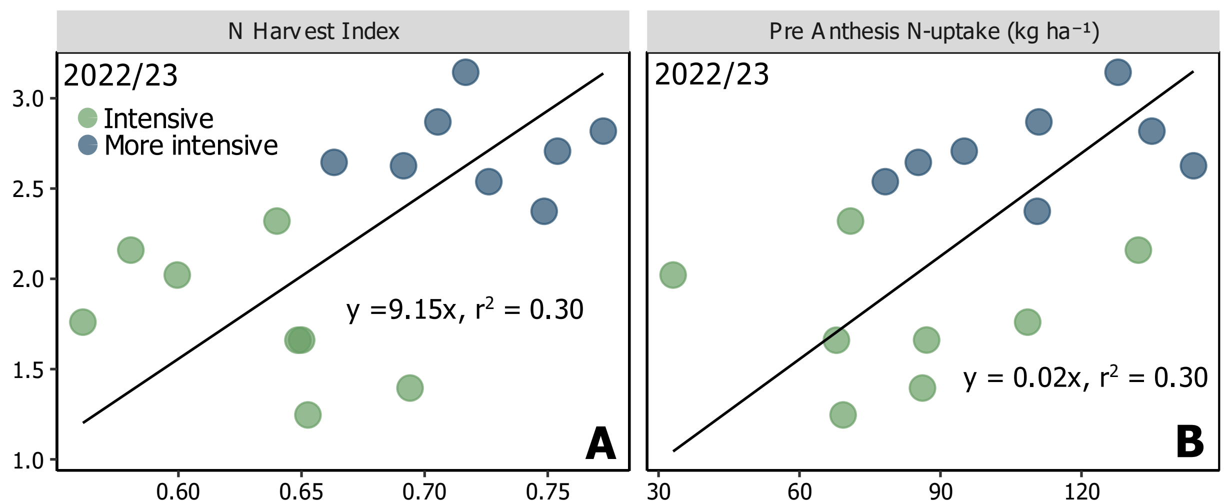

Fig. 3.7 Relationship between grain yield and nitrogen dynamics of winter wheat of Intensive and More intensive systems during 2022/23 growing season in Ashland Bottoms, KS.

Nitrogen by crop sequence interaction

Significant interaction between N management and crop sequence was only observed in the second year (Table 3.2), in which Baseline differed from all other crop sequences under Standard N-management. Wheat grown in the Baseline system had greater grain yield (4.3 vs.

3.5 Mg ha^{-1}, respectively) than all Standard systems partially due to greater whole plant N-uptake, grain N uptake, and post-anthesis N uptake (Fig. 3.8 A-C). No differences occurred between Standard and Progressive N-management either under grain-only or dual-purpose systems.

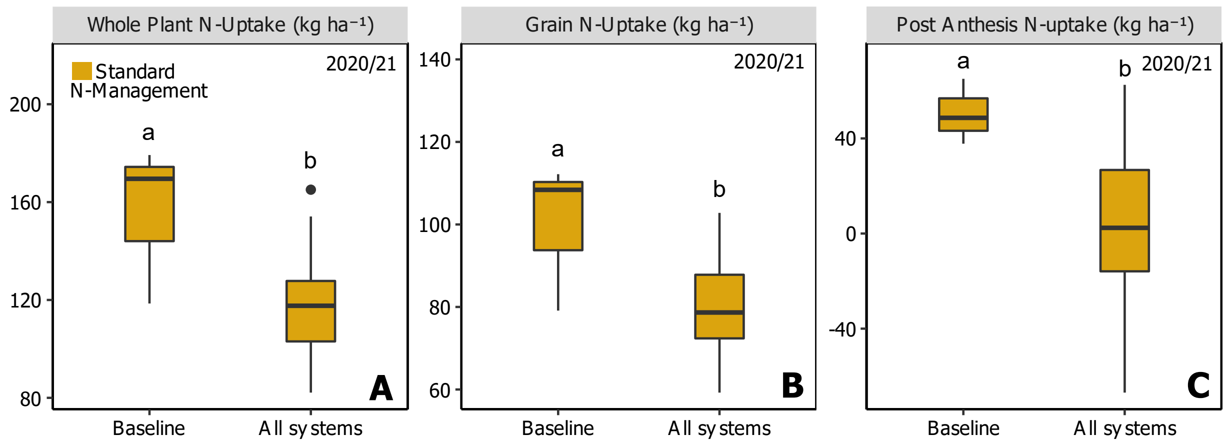

Fig. 3.8 Winter wheat N-uptake by the whole plant (A), by the grain (B), and post-anthesis (C) under Standard N-management of Baseline (i.e., continuous winter wheat - summer fallow), and systems with other crops in the rotation during 2020/21 in Ashland Bottoms, KS.

Modulation of grain yield through yield components

Data normalized within years provided some empirical evidence for the main drivers of wheat grain yield during the study period across N-management and cropping system intensity (Fig. 3.9). Among the yield components, heads m^{-2}, and kernels m^{-2} had high positive correlation with wheat yield and kernels head^{-1} and thousand kernel weight had lower though still significant (R2 = 0.06-0.08). Wheat yield was positively related to biomass production and all N dynamics variables, except post-anthesis N-uptake. Although the relationship between yield and N harvest index and internal efficiency was significant, they had low correlation (R2 = 0.05 and 0.03, respectively). There was no relationship between grain yield and grain protein concentration. Water stress index negatively impacted yield, although their correlation was low (R2 = 0.07). These results were confirmed by a PCA analysis (Supplement Fig. B3).

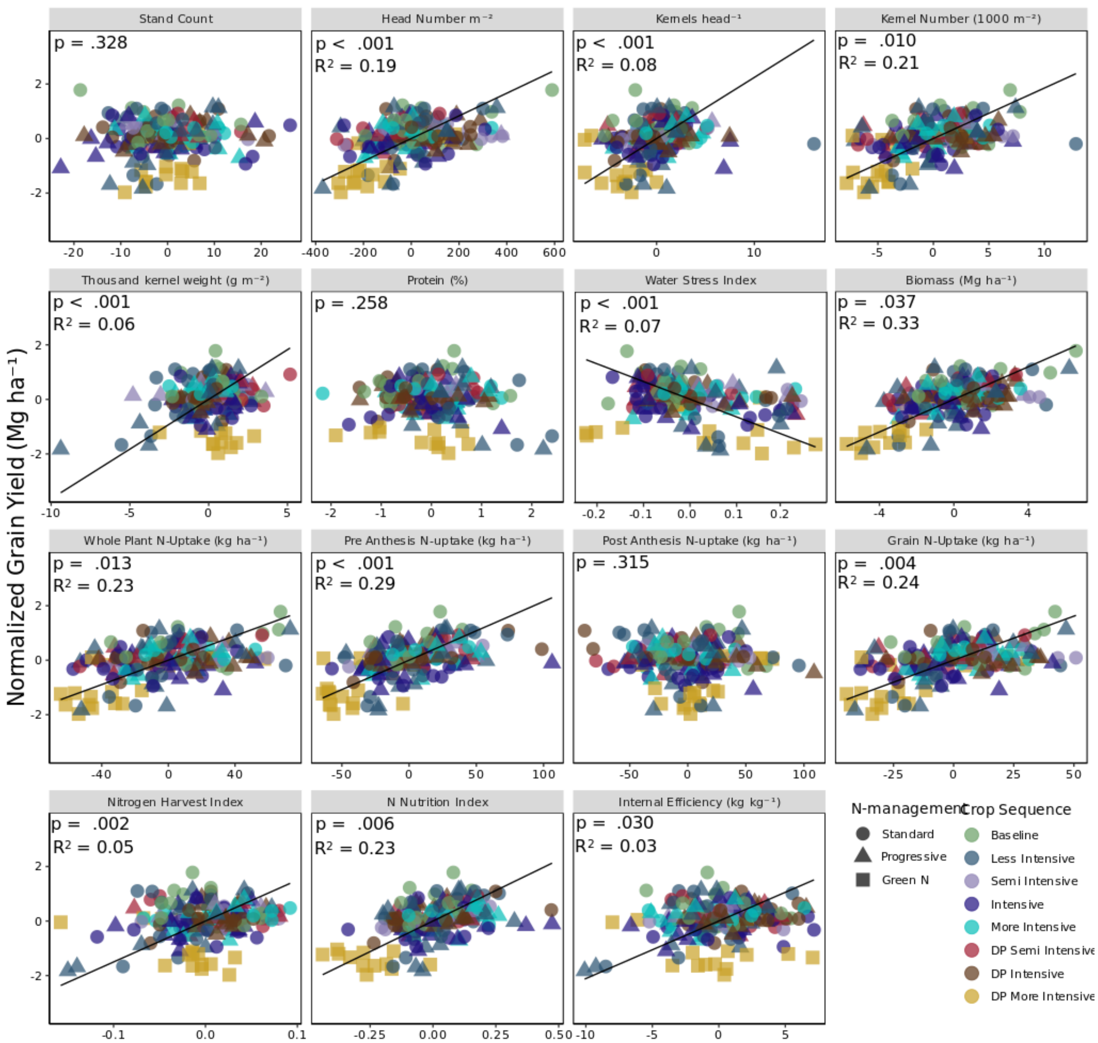

Fig. 3.9 Linear relationships between normalized winter wheat grain yield and normalized independent variables across three different N-management and nine cropping systems intensity during four growing seasons (2020-2023) in Ashland Bottoms, KS.

Discussion

Field experiments conducted during four consecutive seasons created a wide range of environmental conditions for the wheat phase of the rotation through cropping systems of different purposes, intensities, and contrasting N-managements, highlighting the physiological mechanisms behind wheat yield responses to cropping system intensification.

The combination of years and cropping systems resulted in a wide range of water stress index and temperatures experienced during the critical period. This implies that that crop response to temperature fluctuation in this experiment was perhaps not consistent, impacted by water availability (Cossani and Sadras, 2021). We note that factors such as crop type, soil moisture conditions, and crop management practices may influence how crops respond to changes in temperature (Sadras et al., 2022), which in turn was confounded with water stress index in the current experiment.

Relative grain yield responded quadratically to sowing date across seasons and cropping systems, with an optimum sowing date for the study region of DOY 296, which aligns with previous studies on winter wheat (Jaenisch et al., 2021; Munaro et al., 2020) but differs from summer crops, which seem to show a linear decrease in yield potential with delays in planting (Grassini et al., 2015; Rattalino Edreira et al., 2017). The reasons behind the quadratic response is function of different yield-limiting biotic and abiotic factors (Sacks et al., 2010). Early sowing increases insect pressure and the potential for vectoring of viral diseases (Schmid et al., 2019; Wibberley, 1989; Wiersma et al., 2006); can lead to decreased wheat germination if sowing occurs under high soil temperatures (Smith, 1995); and finally there is the potential for lush biomass production during vegetative stages, potentially causing haying off (van Herwaarden et al., 1998). Late-sown wheat has decreased fall tillering potential (Dahlke et al., 1993) and therefore requires increased seeding rates (Staggenborg et al., 2003), which was accounted for in this study. Some evidence also suggests that late sowing can lead to below-optimum fall root growth, increasing the chances of water deficit and winterkill (Hammon et al., 1999). Finally, in extreme cases, late sowing may result in insufficient time for vernalization (Wiersma et al., 2006), which was not observed in this study.

Grain yield of Progressive N-management outperformed Standard in the fourth year likely due to greater rate of N applied for Progressive, which was confirmed by the greater whole plant N-uptake. While all yield components were statistically similar between the two N-management approaches, Progressive consistently displayed higher numerical values across all components except for stand count (refer to Supplement Fig. B3). This marginal increase in yield components collectively likely contributed to the higher grain yield observed with the Progressive method.

There were also no significant differences between the two N management strategies in grain yield in the three initial years of the study. It is important to highlight that N rates were reduced by 10 kg N ha^{-1} in the Progressive treatment in 2021 and 2022, while grain yields were maintained. This suggests overall a greater fertilizer N use efficiency when adopting the the 4R's components here evaluated. Split N-application (i.e., "right timing") delayed pre-anthesis N-uptake, period in which 50% of final seed weight comes from assimilates stored before seed filling in source limited-environments (Gent, 1994). Increasing N and carbon availability during pre-anthesis also increases kernel numbers based on the resource availability at a given yield level (Sinclair & Jamieson, 2006). It is essential to recognize that a notable advantage of the split application in the Progressive treatment is the ability to adjust the second split application in each growing season with suboptimal yield potential, potentially lowering or omitting second application rate in low-yielding potential years. This flexibility can pose advantages in economic and environmental aspects (Simão et al., 2024), although an economic analysis was not conducted and falls outside the scope of this manuscript.

Soil residual N from legume summer crops in the Green N systems was not sufficient to supply N demand by the following winter wheat crop in the second year of study, evidenced by extremely low N nutrition index values for Green N plots (Fig. 3.5F). Poor stand establishment by legume summer crops (data not shown) and poor adaptation of tepary and moth to the region likely influenced the low soil residual N. The lack of yield drag in Green-N at the beginning of the experiment may be related to the abundant N pool in the soil (Hawkesford, 2014; Devienne-Barret et al., 2000; Meisinger, 1984), and in the last year may be related to low yielding potential of the growing season (Fig. 3.3), which had the greatest water deficit.

Dual-purpose systems had greater grain yield than grain-only systems that were sown late. This greater yield was likely due to the large total number of grain-only crops harvested, under different crop systems and N management strategies - which may have impacted soil water content for having crops with shorter cycle in the field (e.g., triticale hay) (Schlegel et al., 2018). Introducing a summer forage into continuous winter wheat (Baseline vs. Dual-purpose summer forage) reduced wheat grain yield when the preceding crop was forage soybean; however, this yield decrease was not evident when the wheat was preceded by a summer fallow. This implies that soil available water likely limited wheat grain yield when it followed forage soybean, as opposed to summer fallow, despite both treatments being sown on the same day. Similar results of reduced wheat yield following a summer crop were found in the Great Plains due to lower soil water availability at sowing (Holman et al., 2020; Schlegel et al., 2018; Stone & Schlegel, 2006). Conversely, wheat yield was not impacted in rotation with soybean in a long-term experiment in the same region of the current experiment (Simão et al., 2022). Horn et al. (2020) tested different grazeable summer crops ahead of wheat in continuous wheat systems of the US southern Great Plains and demonstrated that greater biomass yields in the summer cover crop reduced yields of the subsequent wheat crop also associated with lower available water at sowing. The higher biomass of Baseline resulted in greater whole plant N-uptake and assimilation within the plant compared to Dual-Purpose summer forage. This observed pattern remained consistent when analyzed across various dual-purpose systems.

Greater grain yield for More intensive systems compared to Intensive under Grain-only purpose was likely due to sowing date in the fourth year – More intensive plots were sown following a full season soybean crop, while Intensive plots were sowed after double-cropped soybean. Expectedly, cropping systems impacted wheat sowing dates and consequently temperatures experienced during the critical period for grain development. Sowing dates affected wheat yield due to modifications in biotic and abiotic stresses that the crop was exposed (Munaro et al., 2020; Jaenisch et al., 2021). From an agronomic perspective, fall tillering is reduced (Dahlke et al., 1993), leading to higher seeding rate requirement (Staggenborg et al., 2003). Low root growth rate during the fall increases the risk of water deficit and winterkill (Hammon et al., 1999). Furthermore, it may cause insufficient time for full vernalization (Wiersma et al., 2006). From a physiological perspective, a late sowing date increased the likelihood of higher temperatures at critical periods for yield determination than optimum sowing. Early flowering has been associated with an increase in wheat yield in the US Great Plains (Donmez et al., 2001).

During heading, grain yield is highly susceptible to stresses such as drought and extreme temperatures (Fischer, 1985). Since the introduction of modern photoperiod insensitive semidwarf wheat cultivars, the vegetative period got shorter because varieties are shorter and produce less biomass during vegetative period (Maeoka et al., 2020), thus heading occurs earlier and grain filling period is longer than true tall varieties (i.e., no Rht dwarfing gene).

Wheat shoot biomass at maturity was positively and highly correlated with grain yield across sources of variation, suggesting that treatments that reduced grain yield also reduced shoot biomass. This is consistent across several studies and reviews (de Oliveira Silva et al., 2020a; Jaenisch et al., 2022; Slafer et al., 2014, 2022). Grain yield was determined by the processes leading to starch deposition in the grain (directly affected by carbon assimilation and accumulation during the grain filling period), and grain protein is determined by the processes leading to protein deposition in the grain (directly affected by N assimilation and accumulation primarily pre-anthesis) (Jenner et al., 1991). Grain yield improvement, either due to genetic or environmental conditions, was related to increases in carbon supply and assimilation, which has been attributed to longer growth periods rather than improvement in carbon assimilation mechanisms by the plant per se (Richardson, 2000), therefore not only biomass production was important, but also the length of growth period after anthesis to improve plant’s ability to assimilate carbon – which in this study was impaired by more intensive systems delaying sowing of winter wheat.

Although thousand kernel weight had a positive relationship with yield, the low correlation indicates that the compensation in grain size does not overcome the loss in kernel number, since the maximum grain volume in wheat was shown to be reached when as little as

30% of dry matter was accumulated – suggesting a sink rather than source limitation (Borrás et al., 2004). Thus, any addition in dry matter accumulated after the maximum volume is reached would not translate into more grain; its accumulation limited to that volume size. In this study, some instances showed that treatments with lower yield had greater thousand kernel weight, perhaps driven by a compensatory mechanism for having fewer kernels (Sinclair & Jamieson, 2008).

Conclusion

This research underscored environmental and physiological factors influencing winter wheat grain yield in response to cropping system intensification. The significance of sowing dates became evident, with optimal timing consistently resulted in higher grain yields, while late sowing dates were associated with temperature-induced yield reductions. The impact of crop sequences on winter wheat yields also emerged from i) crop sequences enabling the sowing of winter wheat near the optimal date led to higher grain yields than other sequences with either early or late sowing dates; ii) when following a summer crop, winter wheat grain yield was reduced. This research emphasized the need for careful consideration in the choice of preceding crops and crop sequence, because it impacts the wheat phase of the rotation in different ways. Ultimately, a holistic approach that integrates tailored N management, precise sowing dates, and strategic crop sequences is crucial for optimizing winter wheat productivity and sustainability in agricultural systems.

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Chapter 4 - Conclusions

The collective insights from these three papers offer a comprehensive understanding of the intricate dynamics involved in wheat cultivation and its impact on cropping systems. The global trend of diminishing wheat cultivation area, often driven by the allure of seemingly more profitable summer crops, was reevaluated considering the extensive benefits that wheat brings to the agricultural landscape. Notably, wheat is revealed as a strategic crop capable of contributing to both tactical and long-term goals, thereby offering flexibility that can positively influence farming operations.

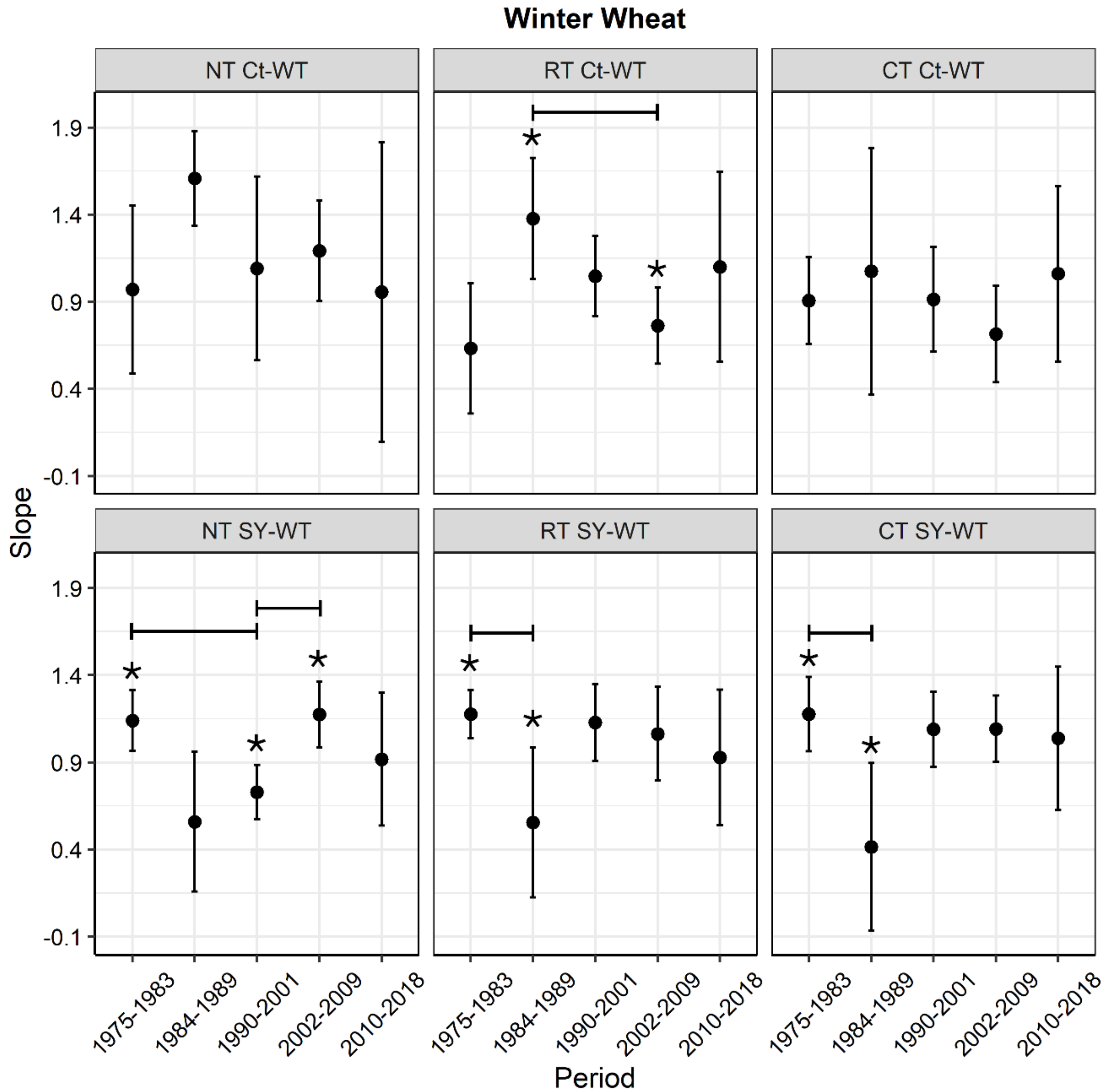
Within various cropping systems, the introduction of wheat is a catalyst for positive change. Beyond its direct contribution to grain yield, wheat demonstrates its value by enhancing agroecosystem diversity, bolstering the resilience of cropping systems against a spectrum of stresses, and curbing the input requirements of other crops. The papers underline the significance of understanding the underlying biological mechanisms responsible for these benefits, providing a roadmap for future research opportunities. Key areas for exploration include the allelopathic potential of wheat against weeds, increased nitrogen availability through rhizodeposition, and the improvement of the composition and longevity of wheat residues.

The second study's emphasis on the long-term benefits of crop rotation and no-till practices further reinforces the idea that sustainable agricultural practices can yield superior results. The advantages of crop rotation, especially when coupled with no-till, extend beyond mere yield improvements, encompassing stability and adaptability across diverse environmental conditions. However, the nuanced relationship between no-till and continuous wheat production warrants a careful consideration of tillage systems based on specific crops.

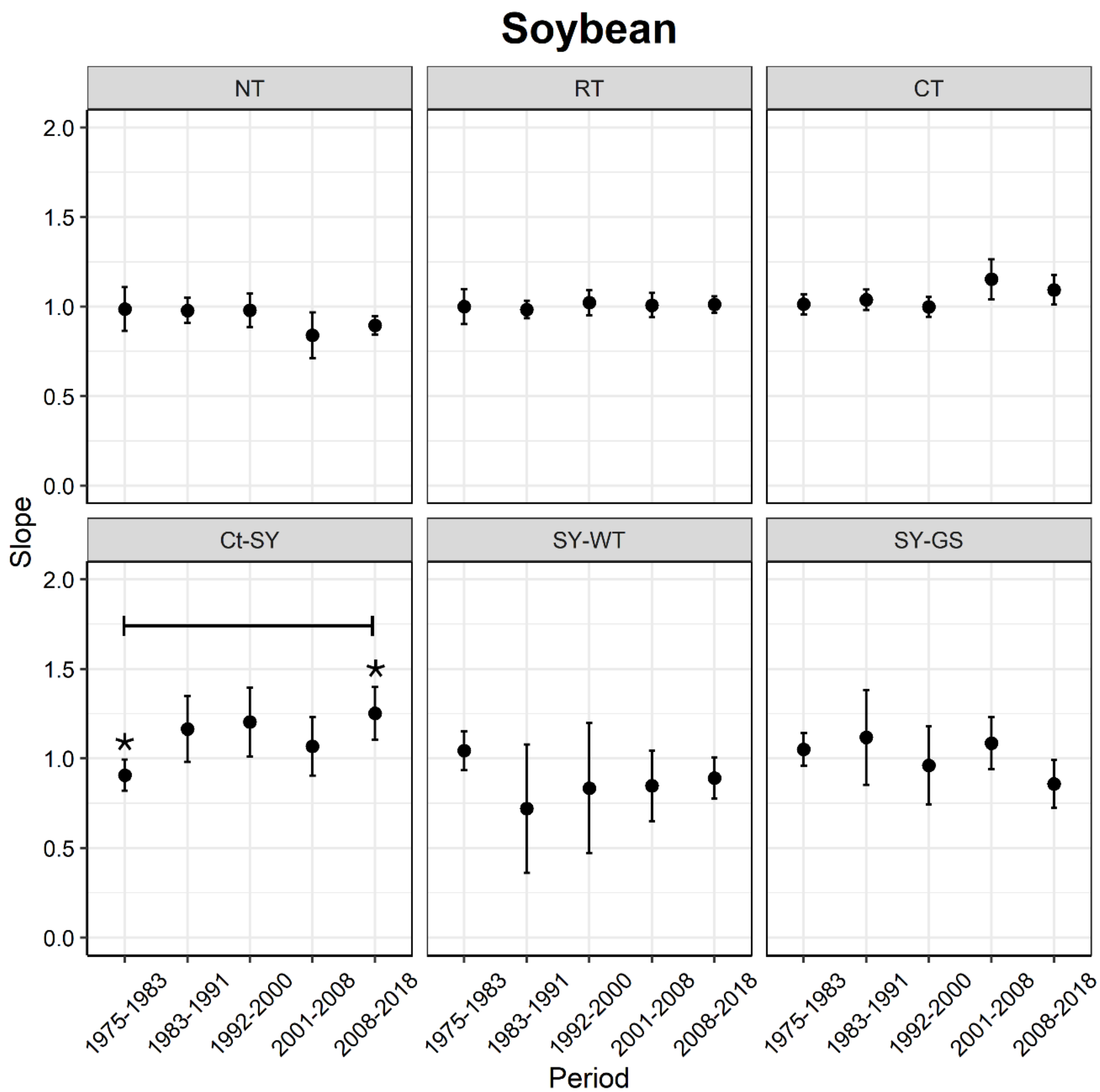
The third paper delves into the intricate factors influencing winter wheat grain yield, highlighting the significance of optimal sowing dates and the choice of preceding crops. A holistic approach, integrating tailored nitrogen management, precise sowing dates, and strategic crop sequences, emerges as imperative for optimizing winter wheat productivity and ensuring the sustainability of agricultural systems.

In conclusion, the synthesis of these studies underscores the importance of promoting wheat cultivation within diversified cropping systems. The strategic integration of crop rotation, no-till practices, and tailored management approaches is essential for addressing current challenges in wheat production and opens avenues for advancing the sustainability and resilience of agricultural systems. The recommendations extend beyond individual studies, advocating for the broader adoption of diversified crop rotations, no-till practices, and meticulous planning of cropping sequences to foster a more sustainable and resilient agriculture while mitigating environmental impacts. These findings contribute to our understanding of wheat's role in sustainable agriculture and provide actionable insights for policymakers, farmers, and researchers aiming to navigate the complex landscape of modern agricultural challenges.

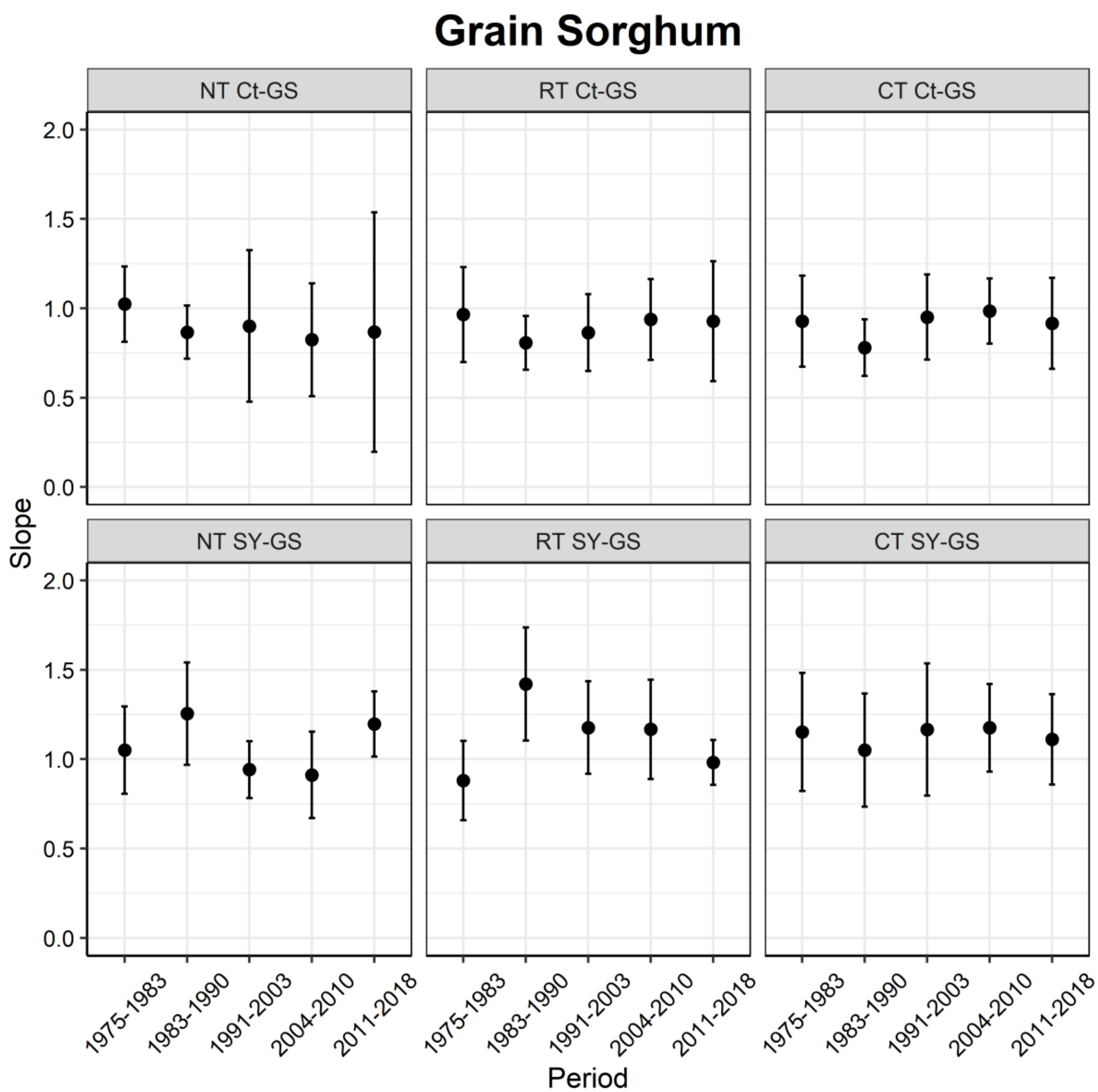
Appendix A - Supplementary Fig.s from Chapter 2



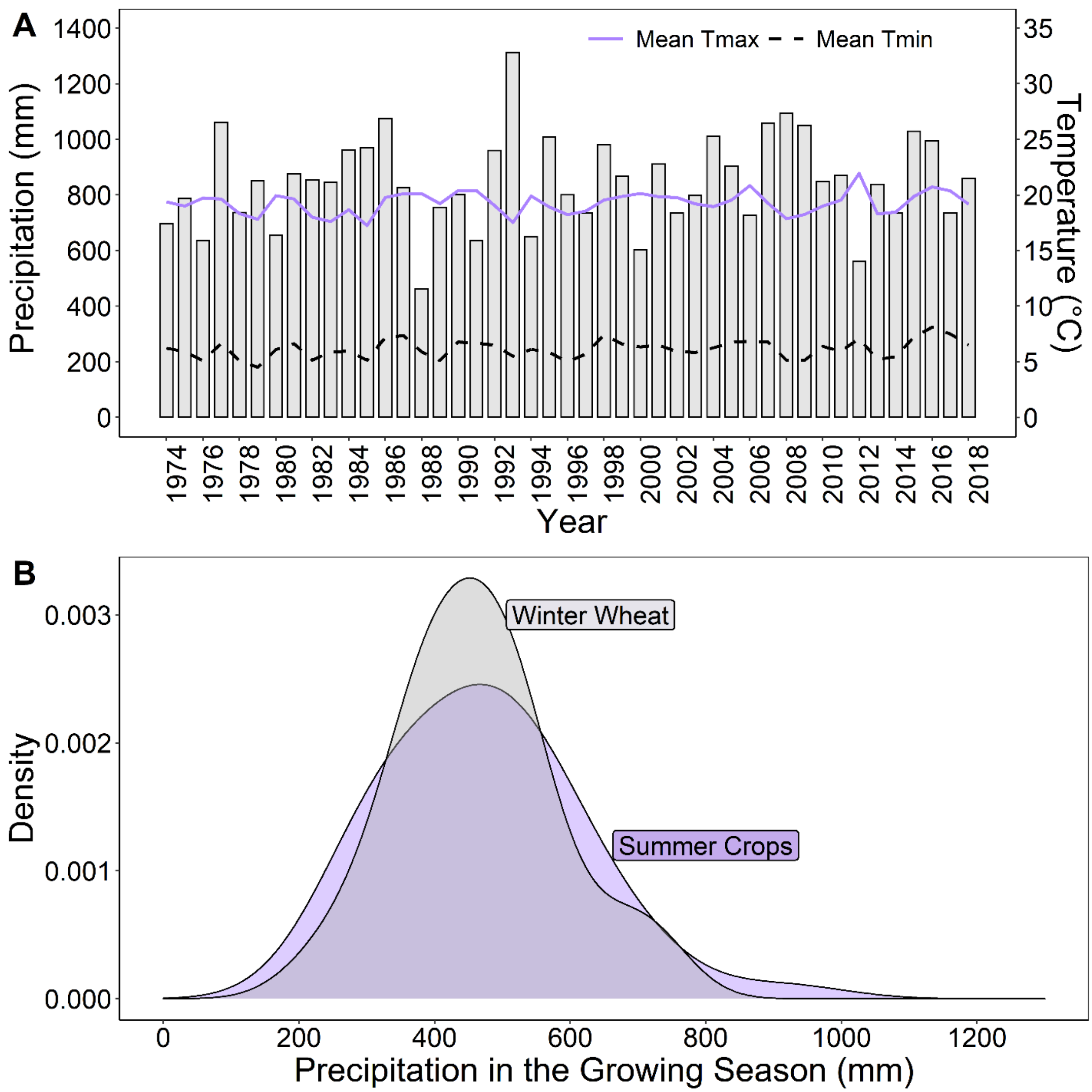
Supplement Fig. A 1 Slopes of linear regression for yield adaptability and stability analysis of winter wheat during five periods from 1975-2018 under different tillage systems (NT = no-tillage, RT = reduced tillage; CT = conventional tillage) and crop sequences (Ct-WT = continuous winter wheat; and SY-WT = soybean-winter wheat rotation;) in a 44-yr study (1974-2018) near Ashland Bottoms, KS, USA. Years were clustered based on winter wheat varieties used over the years, except for 1975-1983 period, which did not have variety record. Pairwise comparison (*) shows significantly differences within periods using 95% confidence interval.



Supplement Fig. A 2 Slopes of linear regression for yield adaptability and stability analysis of soybean during five periods from 1975-2018 under different tillage systems (NT = no-tillage, RT = reduced tillage; CT = conventional tillage) and crop sequences (Ct-SY = continuous soybean; SY-WT = soybean-winter wheat rotation; and SY-GS = soybean-grain sorghum rotation) in a 44-yr study (1974-2018) near Ashland Bottoms, KS, USA. Years were clustered based on soybean cultivars used over the years, except for 1975-1983 period, which did not have cultivar record. Pairwise comparison (*) shows significantly differences within periods using 95% confidence interval.

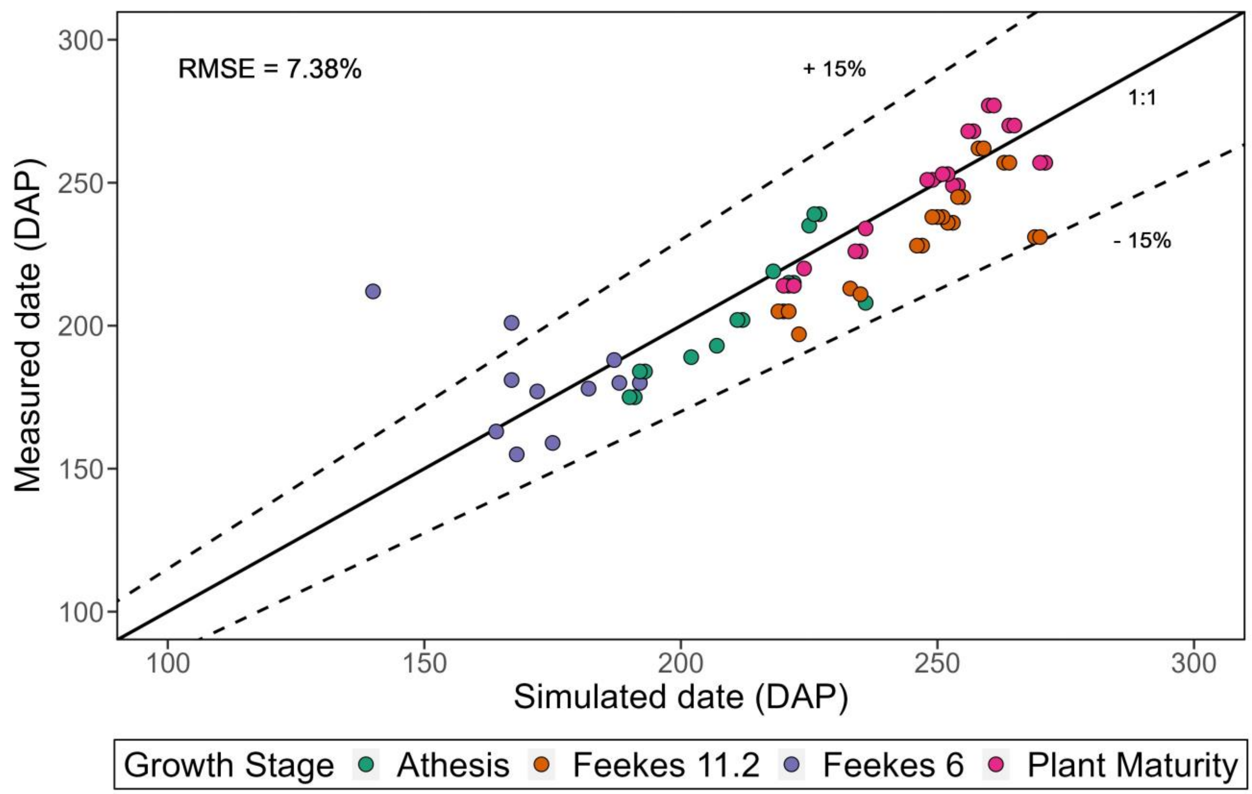


Supplement Fig. A 3 Slopes of linear regression for yield adaptability and stability analysis of grain sorghum during five periods from 1975-2018 under different tillage systems (NT = no-tillage, RT = reduced tillage; CT = conventional tillage) and crop sequences (Ct-GS = continuous grain sorghum; SY-GS = soybean-grain sorghum rotation) in a 44-yr study (1974-2018) near Ashland Bottoms, KS, USA. Years were clustered based on grain sorghum hybrids used over the years, except for 1975-1983 period, which did not have hybrid record.



Supplement Fig. A 4 Yearly precipitation and average maximum and minimum temperatures (A); and density distribution of precipitation (B) during winter wheat and summer crops (soybean and grain sorghum) growing seasons from 1974 to 2018 near Ashland Bottoms, KS, USA.

Appendix B - Supplementary Material from Chapter 3



Supplement Fig. B 1 Validation of Simple Simulation Model (SSM) for phenology in days after planting (DAP) for anthesis, soft dough (Feekes 11.2), jointing (Feekes 6), and plant maturity for winter wheat grown from 2019 to 2022 in the study field. The soil diagonal line represents a 1:1 relationship, dashed lines show ±15% deviation from the 1:1 line. Normalized root mean square error (RMSE) is also shown.

Table B 1 Winter wheat nitrogen management (i.e., rate, timing, source, and placement method) during four growing seasons in Ashland Bottoms, KS.

Growing season	Nitrogen management	Rate	Application Timing[1]	Source[2]	Placement
2019/20	Standard	90 kg ha^{-1}	Single	UAN	Broadcast
	Progressive	90 kg ha^{-1}	Split	UAN + Additive	Streamer bar
	Green N	0 kg ha^{-1}	-	-	-
2020/21	Standard	90 kg ha^{-1}	Single	UAN	Broadcast
	Progressive	80 kg ha^{-1}	Split	UAN + Additive	Streamer bar

	Green N	0 kg ha^{-1}	-	-	-
2021/22	Standard	90 kg ha^{-1}	Single	UAN	Broadcast
	Progressive	80 kg ha^{-1}	Split	UAN + Additive	Streamer bar
	Green N	0 kg ha^{-1}	-	-	-
2022/23	Standard	90 kg ha^{-1}	Single	UAN	Broadcast
	Progressive	100 kg ha^{-1}	Split	UAN + Additive	Streamer bar
	Green N	0 kg ha^{-1}	-	-	-

Summer crops, forage, and cover crops management

Summer crops succeeding winter fallow, hay-triticale, or cover crops were sown early in the season, specifically around mid-May (Table S2). Conversely, summer crops following a winter wheat crop harvested for grain were planted later, typically in early July, immediately after the harvest. Late planting dates were reserved for cowpea, moth bean, tepary bean, grain sorghum, and maize. The alfalfa crop (treatment 17) was seeded after the winter wheat harvest in 2021 and cultivated until the conclusion of the study in October 2022. Forage soybean, maize, sorghum, cowpea, and soybean were planted with a row spacing of 0.76 m, while moth bean, tepary bean, and alfalfa were at 0.38 m, using a 2-row John Deere 7000® planter (John Deere, Moline, IA, USA).

Forage crops, including alfalfa, triticale, and winter wheat, as well as forage soybean, were mowed at the late bud (Fick and Mueller, 1989), late boot (Zadoks et al., 1974), and R3 (beginning pod) phenological stages (Fehr and Caviness, 1977), respectively. Moth bean and tepary bean crops were mowed approximately 68 days after planting. The alfalfa crop was mowed once during the seeding year (2021) and four times during the growing season in 2022. In all mowed forage plots, shoot biomass was removed to prevent the confounding effect of crop residue returning to the soil. Finally, triticale, cultivated for cover crop purposes, was chemically terminated at the booting stage using glyphosate two weeks before the planting of summer crops.

Concerning summer crops, a pre-emergence application of flumioxazin, pyroxasulfone, S-metolachlor, atrazine, mesotrione, imazamox, and glyphosate was administered on selective crops, while a post-emergence application of glufosinate-ammonium, flumioxazin, pyroxasulfone, and glyphosate was carried out as needed. Herbicide mixtures were applied during fallow periods to suppress weeds when necessary.

Table B 2 Crop management (sowing date, genotype, and termination date (i.e., killing date for cover crops, mowing date for forage purpose crops, and maturity date for grain purpose crops) description for nine cropping sequences in experiments conducted from October 2019 to October 2022.

Season	Crop	Crop management		
		Sowing date	Genotype	Termination date
2019/20	Triticale	10/24/19		5/12/20
2020	Soybean	7/8/20		10/20/20
2020	Sorghum	7/8/20		11/3/20
2020	Soybean	7/8/20		10/20/20
2020	Cowpea	7/8/20		10/20/20
2020	Soybean	5/22/202		10/1/20
2020	Moth	7/8/20		10/20/20
2020	Tepary	7/8/20		10/20/20
2020	Forage soybean	7/8/20	Large Lad RR™	9/24/20
2020/21	Triticale	9/24/20		5/6/21

2021	Maize	7/6/21		10/29/21
2021	Soybean	5/14/21		9/21/21
2021	Soybean	7/6/21		10/6/21
2021	Soybean	5/14/21		9/21/21
2021	Forage soybean	7/6/21	Large Lad RR™	9/22/21
2021	Alfalfa	7/6/21	*	9/20/21
2021/22	Triticale	11/8/21		5/11/22
2021/22	Triticale	10/5/21		5/11/22
2021/22	Triticale	10/5/21		5/11/22
2022	Soybean	7/12/22	P40T19E™	10/18/22
2022	Maize	7/12/22	P0622AML™	10/18/22
2022	Soybean	5/17/22	P40T19E™	9/27/22
2022	Forage soybean	7/12/22	Large Lad RR™	10/6/22
2022	Soybean	7/12/22	P40T19E™	10/18/22
2022	Forage soybean	5/17/22	Large Lad RR™	9/15/22
2022	Alfalfa	-	*	**
2022	Forage soybean	5/17/22	Large Lad RR™	9/15/22

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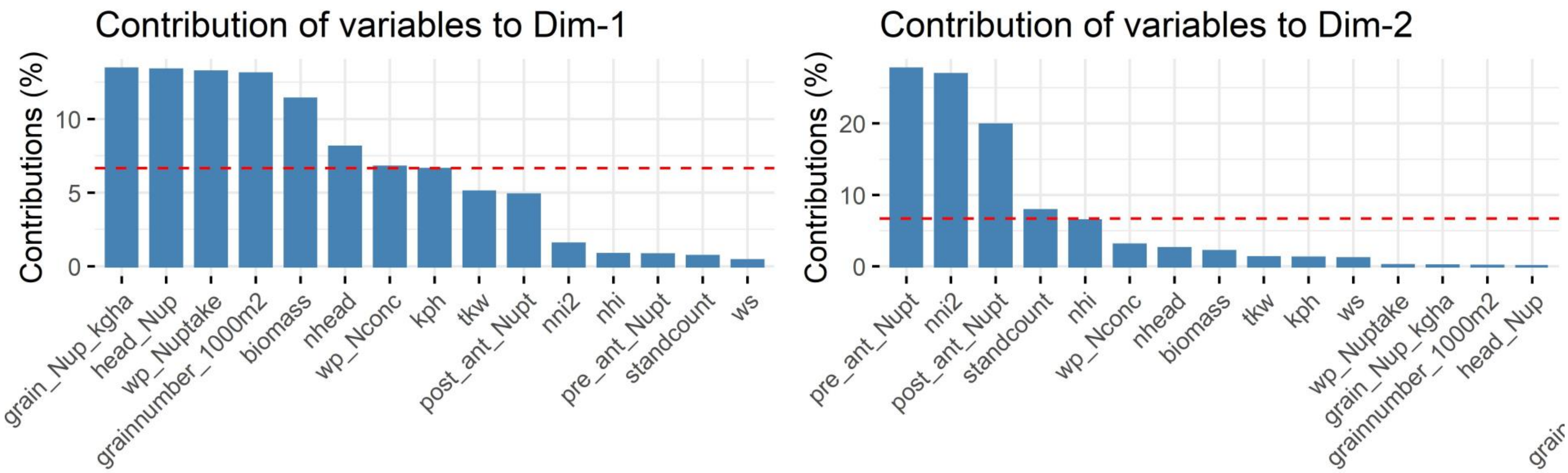
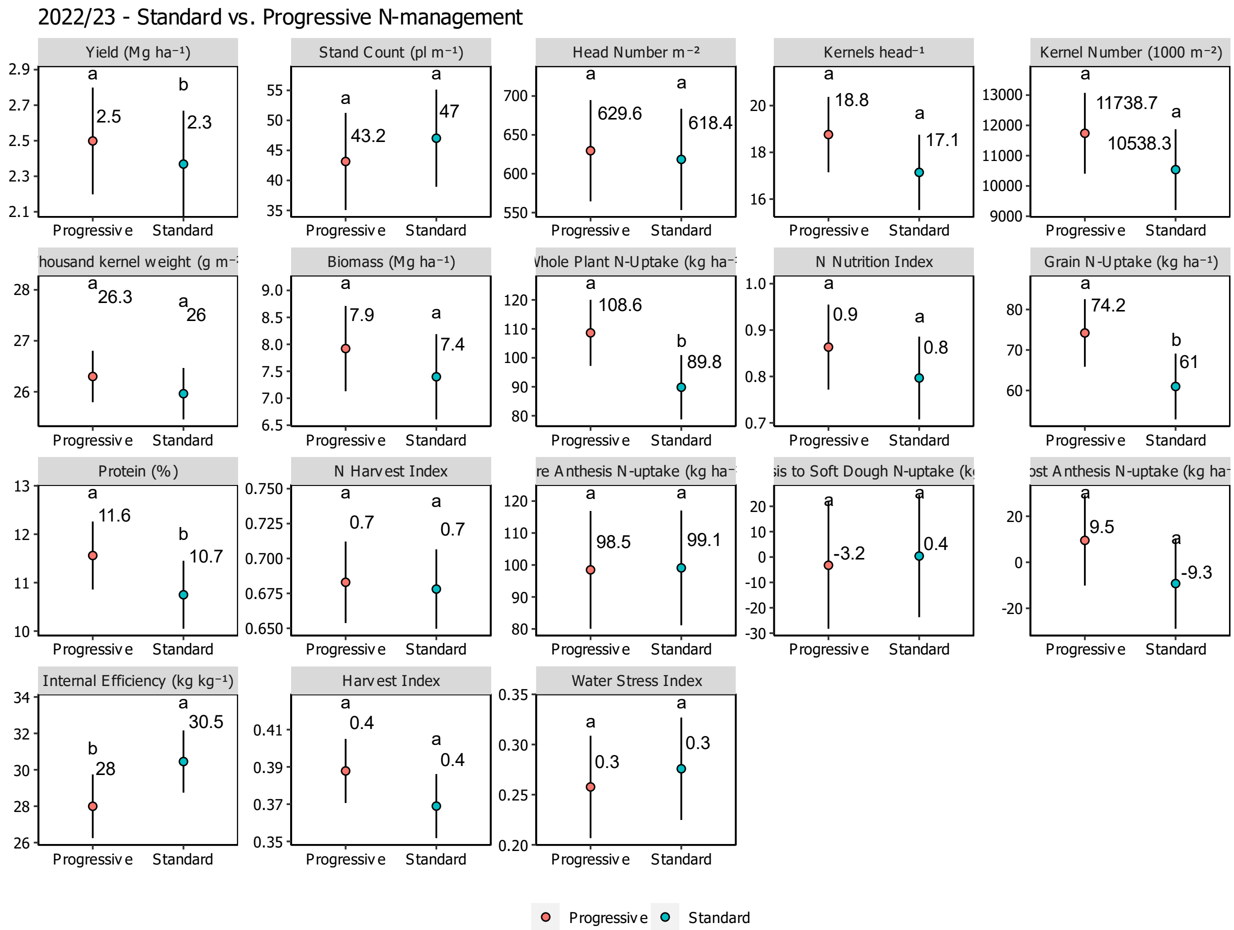
Table B 3 Orthogonal contrasts coefficients of a winter wheat-based cropping system and nitrogen management study in near Ashland Bottoms, KS, during four winter wheat growing season.

			Baseline	*DP Sum For*	Grain Only								Dual Purpose						Total
YEAR 1 (2019/20)		*p-value*			Less intensive		Intensive		Semi intensive		More intensive		DP Semi intensive		DP Intensive		Green N (+ Intensive)		
	N management >		Std	*Pro*	Std	Pro	Std	Pro	Std	Pro	Std	Pro	Std	Pro	Std	Pro	I	II	
Nit	1 Standard vs. Progressive across all treatments	0.875	0	0	-1	1	-1	1	-1	1	-1	1	-1	1			0	0	0
	2 Nitrogen vs. Green N across all treatments	0.786	1	1	1	1	1	1	1	1	1	1	1	1			-6	-6	0
YEAR 2 (2020/21)																			
Nit	1 Standard vs. Progressive across all treatments	0.3881	0	0	-1	1	-1	1			-1	1			-1	1	0	0	0
	2 Nitrogen vs. Green N across all treatments	***0.0293***	1	1	1	1	1	1			1	1			1	1	-5	-5	0
CS	***3 Grain only vs. Dual purpose***	***<.0001***	0	0	0	0	1	1			1	1			-2	-2	0	0	0
	4 Baseline vs. Dual purpose summer forage	***0.0001***	-1	1	0	0	0	0			0	0			0	0	0	0	0
Nit x CS	***5 Baseline vs. all (Standard)***	***<.0001***	-4	0	1	0	1	0			1	0			1	0	0	0	0
	6 Standard vs. Progressive (GO)	0.8131	0	0	1	-1	1	-1			1	-1			0	0	0	0	0
	7 Standard vs. Progressive (DP)	0.0677	0	0	0	0	0	0			0	0			-1	1	0	0	0
PD	***8 Optimum vs. Late***	***<.0001***	1.5	1.5	1.5	1.5	-1	-1			-1	-1			-1	-1	0	0	0
YEAR 3 (2021/22)																			
Nit	1 Standard vs. Progressive across all treatments	0.9651	0	0	-1	1	-1	1	-1	1			-1	1	-1	1			0
CS	2 Grain only vs. Dual purpose	0.264	0	0	1	1	1	1	1	1			-1.5	-1.5	-1.5	-1.5			0
	3 Baseline vs. Dual purpose summer forage	0.112	1	-1	0	0	0	0	0	0			0	0	0	0			0
	4 Semi intensive DP vs. Intensive DP	0.2474	0	0	0	0	0	0	0	0			1	1	-1	-1			0
Nit x CS	5 Baseline vs. all (Standard)	0.1889	-5	0	1	0	1	0	1	0			1	0	1	0			0
	6 Standard vs. Progressive (GO)	0.4835	0	0	1	-1	1	-1	1	-1			0	0	0	0			0
	7 Standard vs. Progressive (DP)	0.3522	0	0	0	0	0	0	0	0			-1	1	-1	1			0
PD	***8 Optimum vs. Late***	***<.0001***	2	2	-3	-3	2	2	-3	-3			2	2	0	0			0
YEAR 4 (2022/23)																			
Nit	***1 Standard vs. Progressive across all treatments***	***0.0094***	0	0	-1	1	-1	1			-1	1			-1	1	0		0
	2 Nitrogen vs. Green N across all treatments	0.1298	1	1	1	1	1	1			1	1			1	1	-10		0
CS	3 Baseline vs. Dual purpose summer forage	0.9545	-1	1	0	0	0	0			0	0			0	0	0		0
	4 Intensive vs. More intensive GO	***0.0014***	0	0	0	0	1	1			-1	-1			0	0	0		0
	5 Intensive GO vs. Intensive DP	***0.02***	0	0	0	0	1	1			0	0			-1	-1	0		0
Nit x CS	6 Baseline vs. all (Standard)	0.8997	-4	0	1	0	1	0			1	0			1	0	0		0
	7 Standard vs. Progressive (GO)	0.9289	0	0	1	-1	1	-1			1	-1			0	0	0		0
	8 Standard vs. Progressive (DP)	0.071	0	0	0	0	0	0			0	0			-1	1	0		0
PD	***9 Optimum vs. Late***	***0.0001***	1	1	1	1	-1.5	-1.5			1	1			-1.5	-1.5	0		0

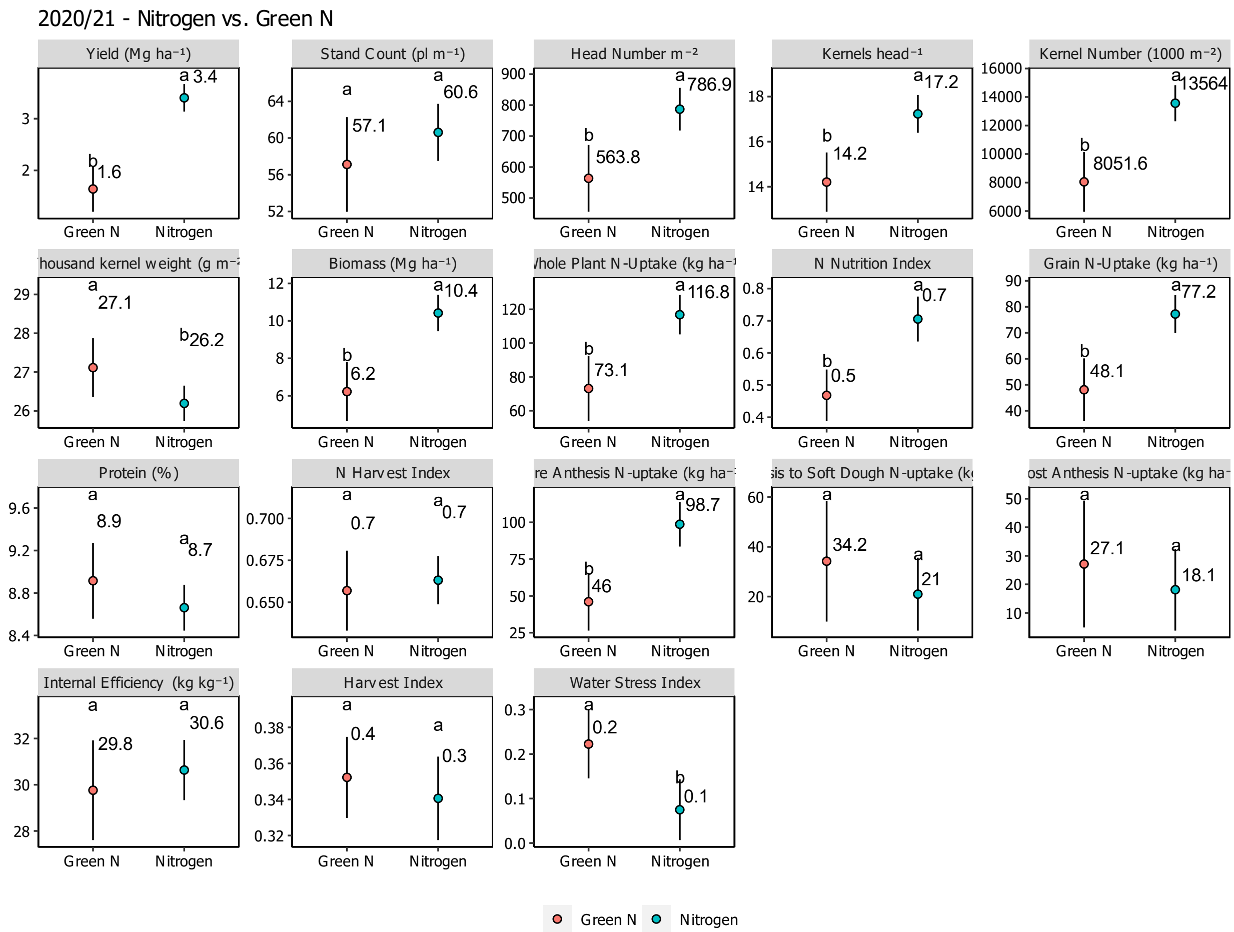
[1]DP = dual-purpose; GO = grain-only, Std = Standard N-management; Pro = Progressive N-management; Sum For = Summer forage.



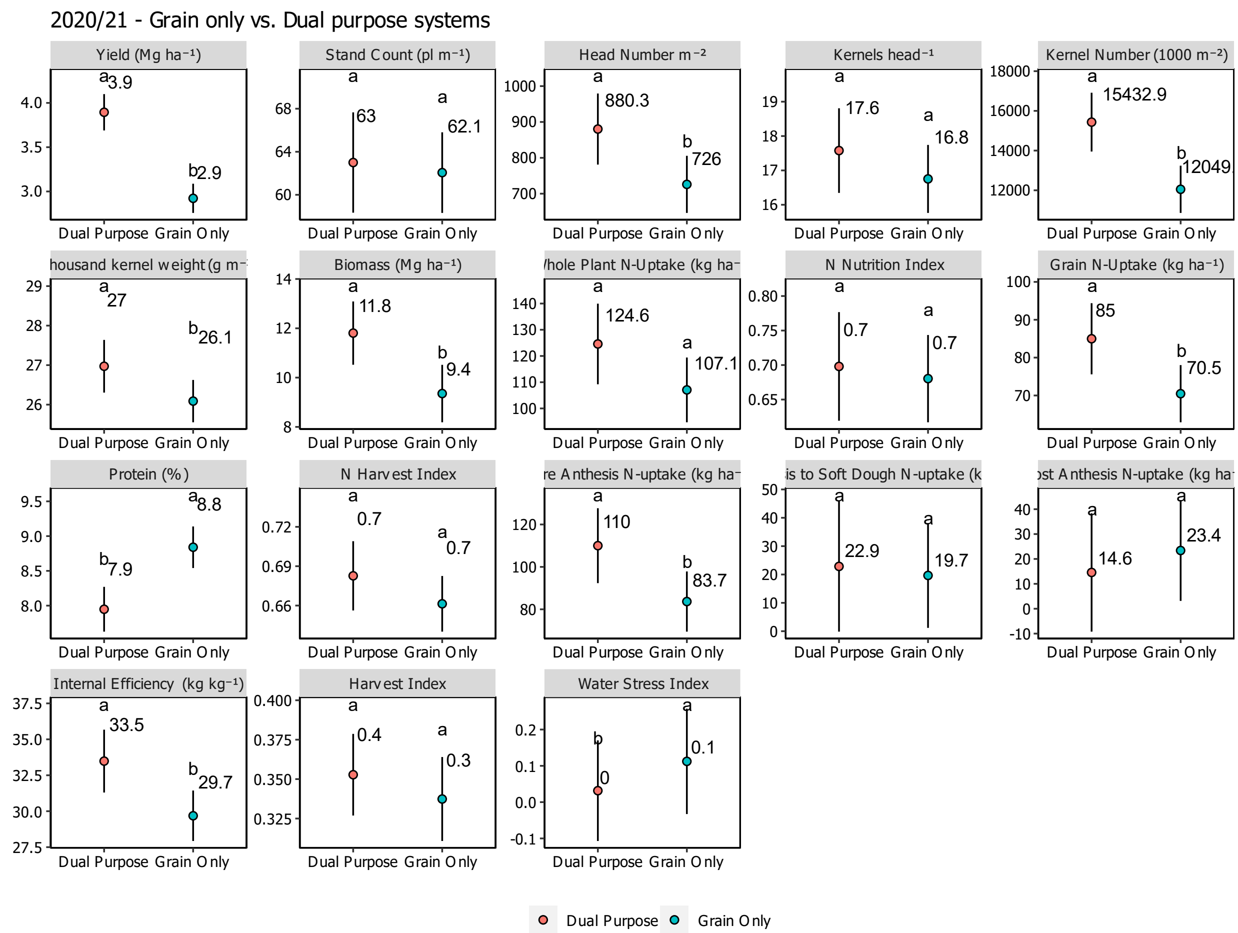
Supplement Fig. B 2 Principle component analysis (PCA) of nitrogen dynamics and yield components on grain yield of winter wheat during 2019-2023 near Ashland Bottoms, KS. (Abbreviations: kgha = kg ha^{-1}, Nup = nitrogen uptake; wp = whole plant; nhead = number of head; Nconc = nitrogen concentration; kph = kernel per head; tkw = thousand kernel weight; ant = anthesis; nni2 = nitrogen nutrition index; nhi = nitrogen harvest index; ws = water stress index).



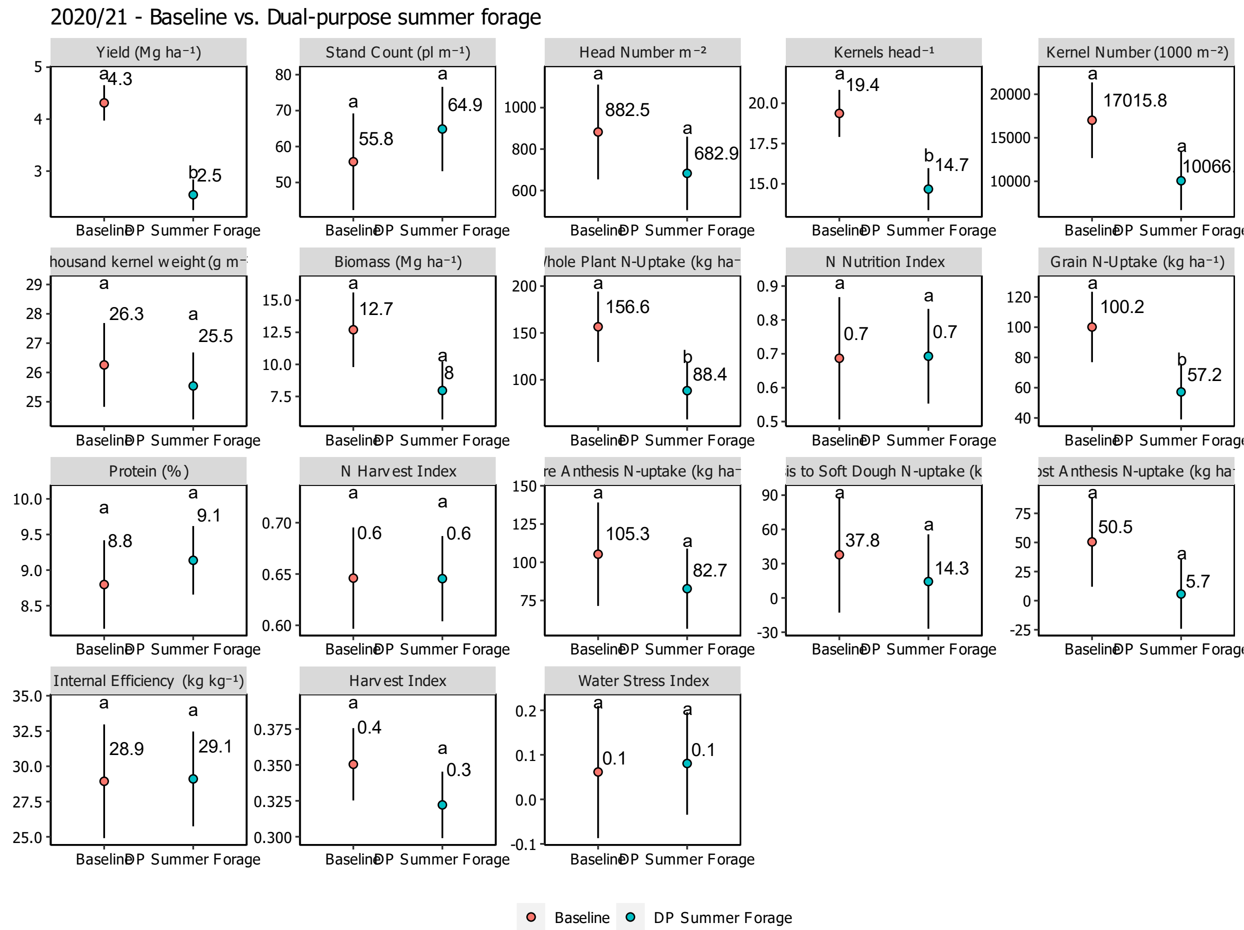
Supplement Fig. B 3 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Standard and Progressive N-management across six cropping systems near Ashland Bottoms, KS, for 2022/23 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



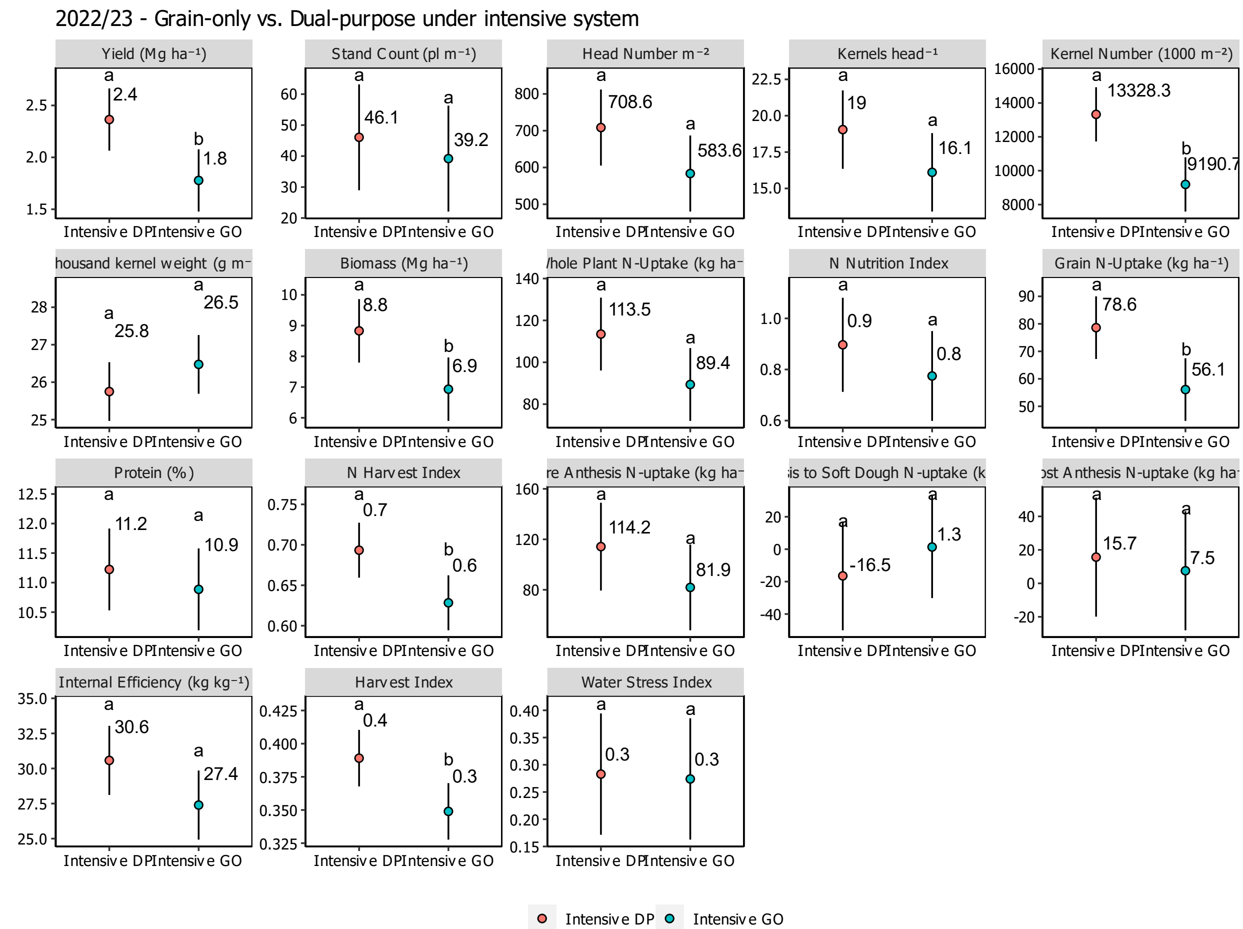
Supplement Fig. B 4 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Nitrogen applied and Green N N-management across ten cropping systems near Ashland Bottoms, KS, for 2020/21 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



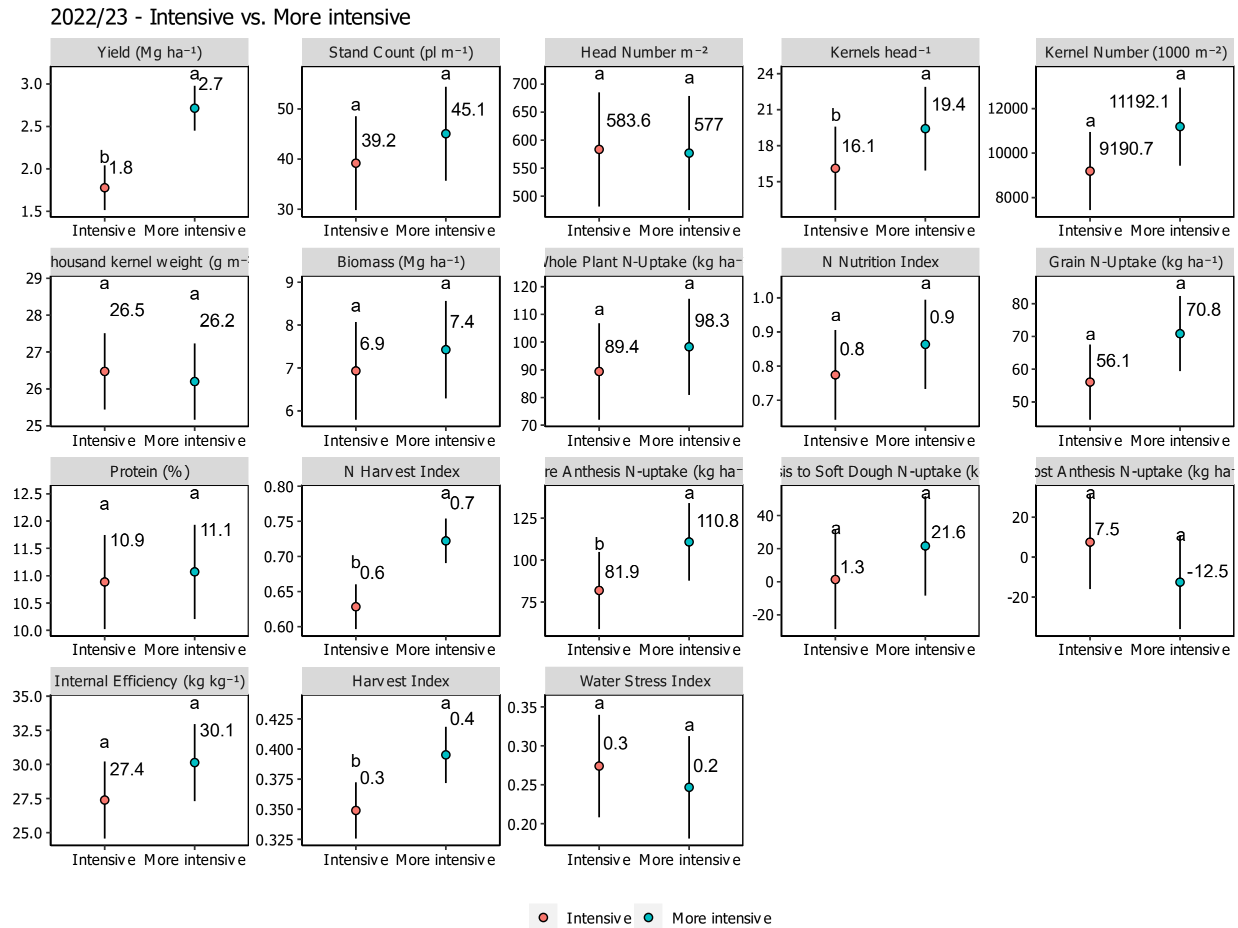
Supplement Fig. B 5 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Grain-only and Dual-purpose across six cropping systems near Ashland Bottoms, KS, for 2020/21 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



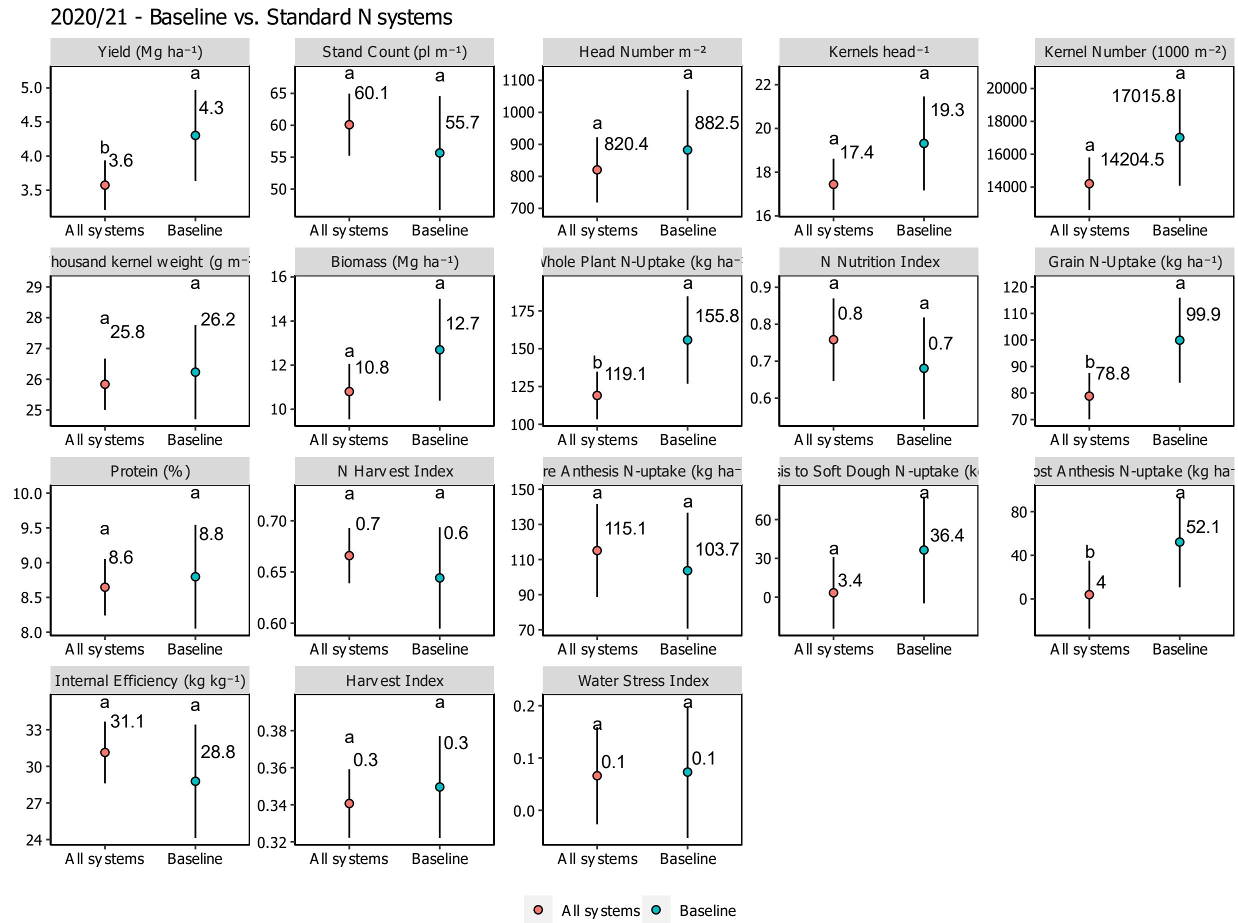
Supplement Fig. B 6 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Baseline and Dual-purpose summer forage near Ashland Bottoms, KS, for 2020/21 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



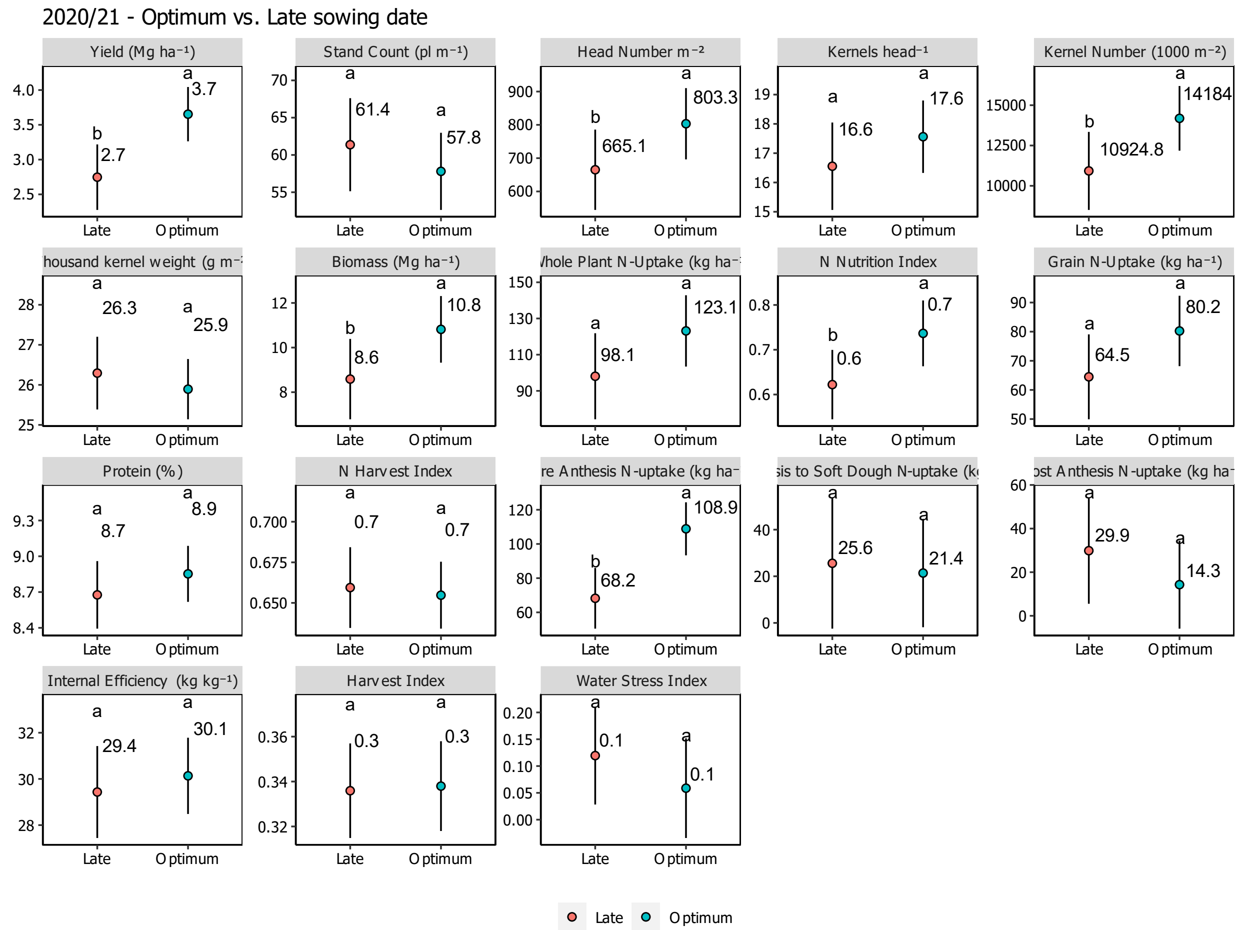
Supplement Fig. B 7 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Grain-only and dual-purpose intensive systems near Ashland Bottoms, KS, for 2022/23 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



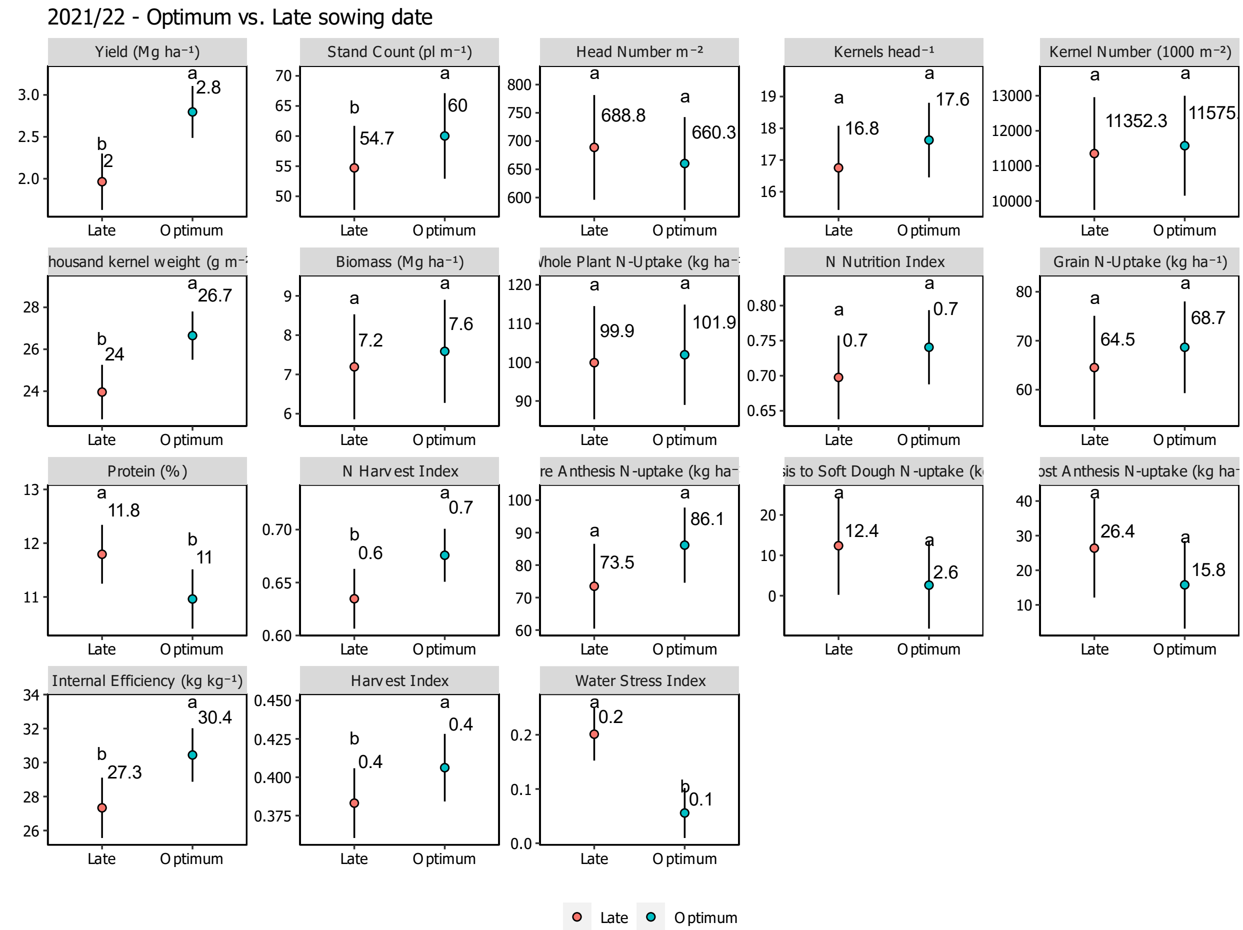
Supplement Fig. B 8 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Intensive and More intensive systems near Ashland Bottoms, KS, for 2022/23 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



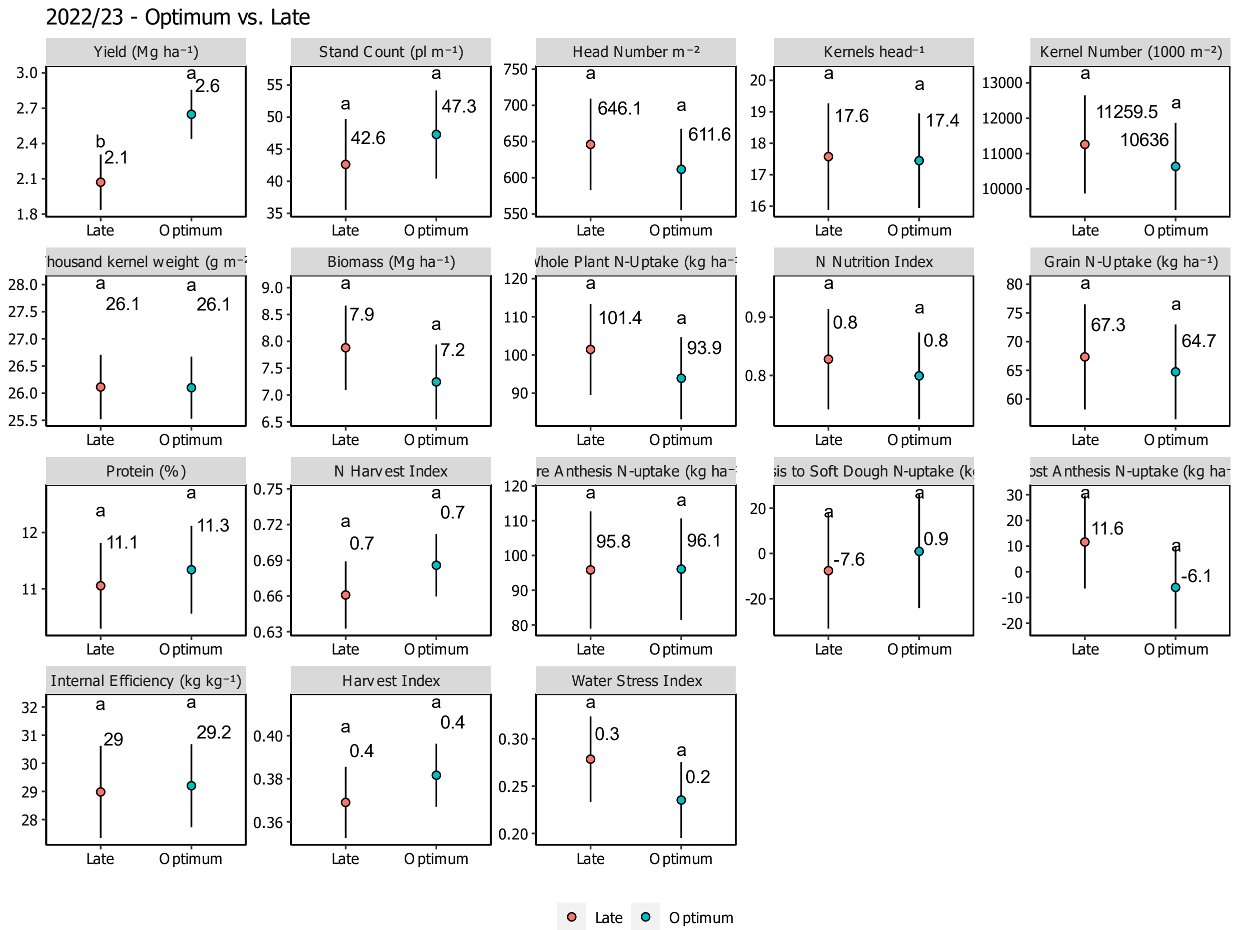
Supplement Fig. B 9 Winter wheat independent variables including grain yield, yield components, and N-dynamics of five cropping systems and Baseline system, both under Standard N-management, near Ashland Bottoms, KS, for 2022/23 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



Supplement Fig. B 10 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Optimum and Late sowing dates near Ashland Bottoms, KS, for 2020/21 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



Supplement Fig. B 11 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Optimum and Late sowing dates near Ashland Bottoms, KS, for 2021/22 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.



Supplement Fig. B 12 Winter wheat independent variables including grain yield, yield components, and N-dynamics of Optimum and Late sowing dates near Ashland Bottoms, KS, for 2022/23 winter wheat growing season. Different letters indicate that means are statistically different at α = 0.05 level of significance. Errors bars represent mean standard error.