CHAPTER TWO

Beyond grain: Agronomic, ecological, and economic benefits of diversifying crop rotations with wheat

Luana M. Simão[a], Giovana Cruppe[b], J.P. Michaud[c], William F. Schillinger[d], Dorivar Ruiz Diaz[a], Anita J. Dille[a], Charles W. Rice[a], and Romulo P. Lollato[a,*]

[a]Department of Agronomy, Kansas State University, Manhattan, KS, United States
[b]Department of Plant Pathology, Kansas State University, Manhattan, KS, United States
[c]Department of Entomology, Kansas State University, Agricultural Research Center, Hays, KS, United States
[d]Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, Lind, WA, United States
*Corresponding author: e-mail address: lollato@ksu.edu

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Abstract

Global wheat production has remained stable in the last 20 years, benefiting from increased grain yields despite 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 the 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 the 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 on 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 population; and (vi) decrease variability in economic returns. This review highlights that 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.

Abbreviations

C carbon
GHG greenhouse gases
N nitrogen
P phosphorus
PUE precipitation use efficiency
PA precipitation allocation
SCN soybean cyst nematode
SOC soil organic carbon

1. 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.

2. 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 sustainable increases in crop productivity (Cassman and 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 (Júnior 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 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 and 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 and 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). This decrease in wheat area is mainly attributable to the advent of new technologies that have made other crops more attractive to farmers (e.g., pesticide and/or drought-tolerant crops; Cooper et al., 2014), changes in local land use policies (Anderson et al., 2001), and volatile wheat prices (Deen et al., 2016; Mulik, 2015). When international prices of wheat become more volatile, farmers tend to allocate less land to wheat or reducing 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 years maize-soybean rotation, as highlighted in a number of 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 that crop diversification enhances cropping systems resilience. However, whereas many US farmers acknowledge the advantages of diversifying a 2-year 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 widely adaptable to many environments (Acevedo et al., 2002).

3. 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 or even negative effects.

3.1 Wheat as a versatile crop

Early wheat growth prior to the critical period of yield determination (i.e., from onset of stem elongation until ~10 days post anthesis, when grain number is defined; Fischer, 1985) is not as important for grain yield as the duration, growth rate, and partitioning of resources during the critical period (Slafer et al., 2023). The reduced importance of early vegetative growth to grain yield provides flexibility in management and crop utilization alternatives (Fig. 1).

3.1.1 Tactical in-season management

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

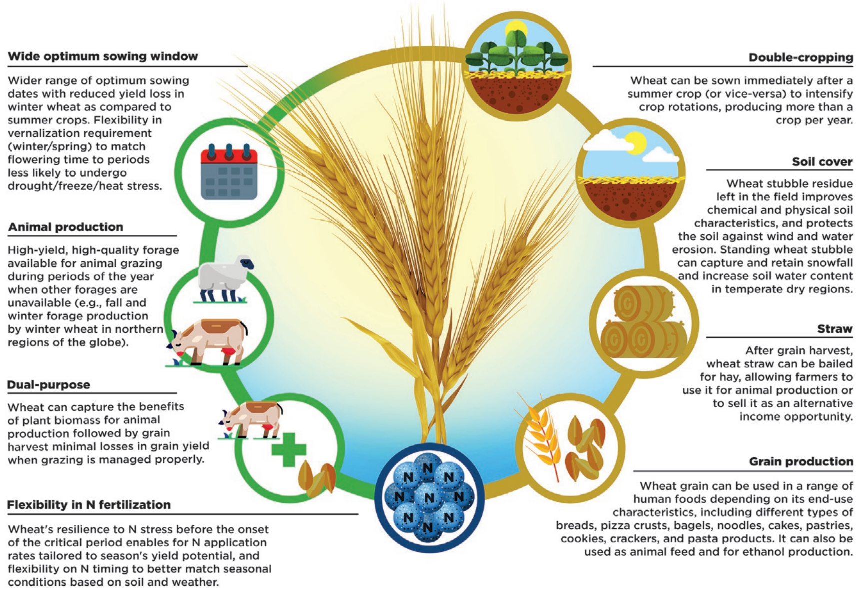

Fig. 1 Schematic representation of the uses and opportunities of wheat in a farming system.

wheat—as much as a 50–66 days range—where the loss in yield potential is less than 8–13 $kg\,ha^{-1}\,day^{-1}$ (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). A wider optimum window allows growers to target sowing during periods of appropriate conditions for crop emergence, which often vary along geographic gradients (Lollato et al., 2021), improving the probability of good stand establishment and high yield potential.

In some regions, the cultivation of either spring or winter wheat genotypes offer additional flexibility (e.g., Cann et al., 2020; Entz and Fowler, 1991; Koppel et al., 2020; Krato and Petersen, 2012; Stoskopf et al., 1974), and provides opportunities to capitalize on optimum sowing conditions for either of 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 to occur 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 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 actually improved N use efficiency in some cases. These findings have been replicated elsewhere (e.g., 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 yield potential of a field showing symptoms of N deficiency (Fig. 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 from 60 to 117 days after N deficiency symptoms were first observed. The experiment was conducted in 12 Oklahoma (USA) environments in which the yield of the unfertilized control (Y_0) ranged from 1.3 to 3.5 $Mg\,ha^{-1}$, and was expressed relative to yields in the fall-applied N treatment (Y_N) [calculated as $y = 100\ (Y_N - Y_0)/Y_0$], which ranged from 13% to 172% (Fig. 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 $y = 100\ (Y_t - Y_N)/Y_N$] vs the number of days between N fertilization and the beginning of the critical period (Fig. 2C). The initiation of the critical period was modelled in each site-year using local weather and the 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;

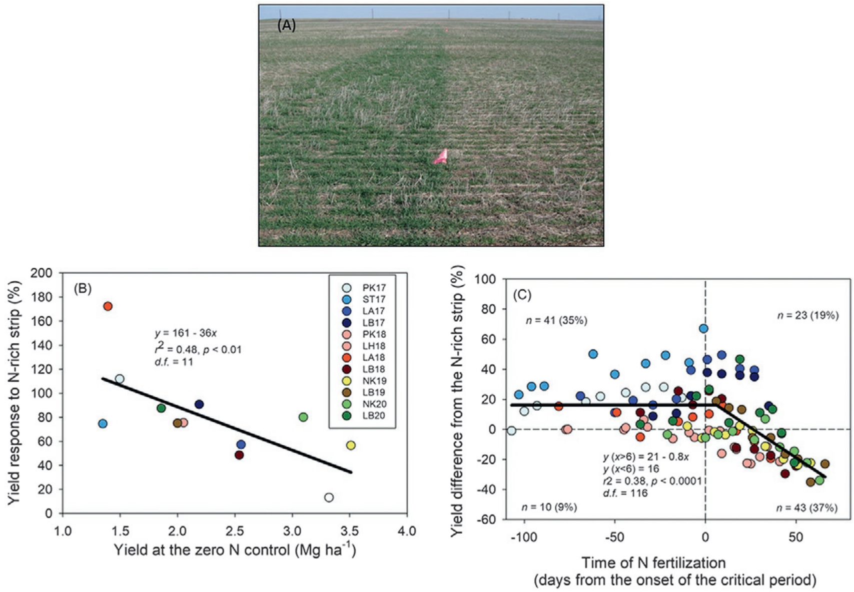

Fig. 2 Wheat can sustain nitrogen (N) deficiency during vegetative stages without yield penalty. (A) Use of N-rich strip technology to determine N rates for wheat using in-season canopy reflectance measurements. This N-management tool makes recommendations for fields that are already N-deficient to aid crop recovery. (B and C) Re-analysis of Souza et al. (2022) data showing (B) yield response to fall-applied N vs the zero N control, as function of zero N control yield, in 12 Oklahoma (USA) 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 function of the time of N fertilization from onset of the critical period in each environment. For experimental description and site-specific details, see Souza et al. (2022). *(Panel A) Photo credit and approval for publication: Dr. Brian Arnall.*

note that in both cases the N was applied to wheat plants that were already N-deficient. The data followed a plateau-linear model, suggesting that N application to N-deficient wheat during the 107-day 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 increases from N fertilizer at a rate of −0.7% day^{-1} (CI: −0.5% to −1.0% day^{-1}) (Fig. 2C). This demonstrates the ability of wheat to handle 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 increases return on 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 that will affect yield potential (Raun et al., 2008).

3.1.2 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 around the world (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 in Mediterranean climatic regions (e.g., Australia, Italy, West Asia, and Africa; Kelman and Dove, 2009), or for a longer duration at a lower stocking rate in the US Great Plains (Holman et al., 2010; Khalil et al., 2002). Winter wheat can produce as much as 3.5 Mg ha^{-1} of high protein dry matter and allow for as many as 120–150 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 small tradeoffs in grain yield, provided that grazing is terminated prior to 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 day^{-1} (Lollato et al., 2017); and for as many as 30 days of grazing by Merino sheep, *Ovis aries*, at 1965 sheep ha^{-1} (Harrison et al., 2011b). This dual-purpose option allows for flexibility to either 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 Jr. et al., 1989).

Another example of the versatility of wheat is its potential to be double-cropped with summer crops, either via delayed sowing after the summer crop (Staggenborg et al., 2003), or by delayed planting of the summer crop after winter wheat (Santos Hansel et al., 2019). This permits 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 adoption of a spring wheat crop sown in the fall can allow for the production of a second cash crop within the same calendar year (e.g., Garbelini et al., 2022). Further, efforts to improve the crop's tolerance to biotic (e.g., Cruppe et al., 2023; Webber et al., 2023) and abiotic factors (Pereira et al., 2019), and to refine agronomic recommendations (e.g., Galindo et al., 2017; Teixeira Filho et al., 2011, 2014) could potentially allow for the cultivation of wheat as a second crop in as many as 4.5–7.9 million hectares in the Cerrado region of Brazil (Pasinato et al., 2018).

3.2 Wheat impacts on the grain yield of other rotational crops

A number of 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-year study in Illinois, USA, by Zacharias and Grube (1984) suggested greater maize and soybean yields in a maize-soybean-wheat rotation compared to systems including only maize and/or soybean. In a long-term study (44 years) in eastern Kansas, Simão et al. (2023) reported a 27% soybean yield increase in rotation with winter wheat as compared to a 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, USA; both maize and soybean had 5–8% yield increase 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 years, showed that 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. $+1.5\,\mathrm{Mg\,ha^{-1}}$) in the maize-soybean-wheat rotation than in continuous maize (Kazula and Lauer, 2018). In Alabama, USA, Edwards et al. (1988) found that soybean yields were 6% greater in a maize-soybean-wheat rotation compared to maize-soybean only. In Indiana, USA, Martin et al. (1991) found greater soybean yields under a soybean-wheat-maize rotation than under soybean-maize, as 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 and 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 3 years (maize-soybean-wheat) increased soybean yield by 0.20 Mg ha^{-1}. Although results were consistent for maize, 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 increased by the addition of wheat to the rotation as compared to continuous plantings of these crops (Fig. 3). The mean difference between maize-soybean-wheat vs maize-soybean, or a monocrop, was positive and significantly different from zero in all instances except for maize under maize-soybean (inset graphs, Fig. 3A and B). In all cases, the slope was not statistically different from one, suggesting that these yield benefits were consistent across yield environments.

In a long-term (14 years) study in Ontario, Canada, the inclusion of wheat in 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). Although high N application rates offset the benefits of including wheat in maize-based rotations to maize yield, maize yields under low N rates were similar to those under high rates when wheat was included in the rotation. Thus, inclusion of wheat in maize-based systems decreased 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 years) 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 et al., 2019b). Harker et al. (2015) observed that inclusion of spring

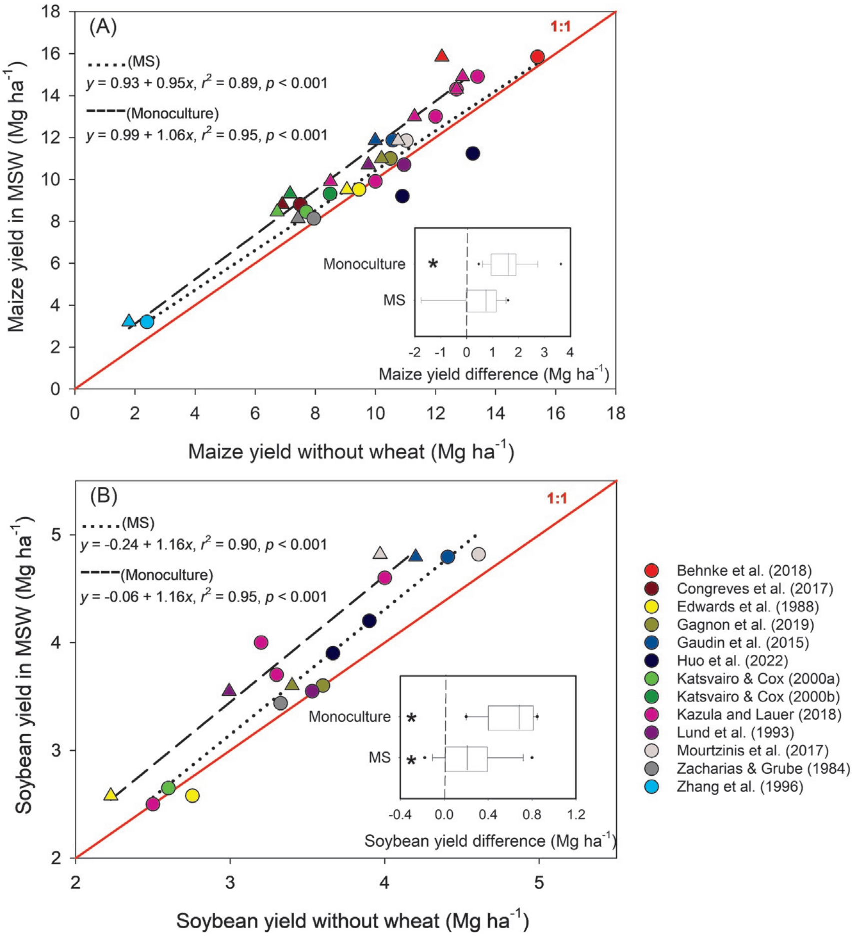

Fig. 3 Yield of (A) maize and (B) soybean when wheat (MSW, maize-soybean-wheat) is included in the rotation, compared to systems without wheat (MS, maize-soybean, dotted lines; and monoculture of soybean or corn, dashed lines) grown in the same experiments. Each symbol represents the overall effect of 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 ($\alpha = 0.05$).

wheat in the system increased canola yields in dryland regions of western Canada compared to continuous canola. In the study, for each annual increase in the number of crops between canola cycles, canola yield increased from 0.20 to 0.36 $Mg\,ha^{-1}$. Likewise, O'Donovan et al. (2014) suggested that canola yields decreased 9% under continuous canola when compared to a canola–spring wheat rotation, also with promising results when canola followed faba bean, *Vicia faba* L. In both studies, wheat served to break canola disease cycles, which boosted canola yields.

3.3 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. In New York, a 6 years study by Singer and Cox (1998b) of crop rotations lengthening 2 years compared maize after either maize, soybeans, or wheat interseeded with red clover, under both high and low chemical (e.g., herbicide) management regimes. 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 conditions (Hegewald et al., 2018). Yield improvements following wheat were the result of small increases in multiple components of canola yield such as plant population, number 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 on 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-year study in semiarid western Kansas, USA, 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. These yield improvements associated with greater available water at sowing for the summer crops when following winter wheat vs when following a previous summer crop. Similarly, a 24-year study in semiarid eastern Colorado, USA, 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 and Vigil, 2018). Long fallow periods (10–11 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.

3.4 Benefits of wheat for cropping system resilience and stability

Diversification of simple crop rotations (i.e., one or two crops per rotation) by addition of wheat can enhance yield stability of the other crops in the system, in addition to increasing grain yields. For example, Simão et al. (2023) concluded that soybean in rotation with winter wheat had greater yield and yield stability compared to continuous soybean over a 44-year period. This benefit was irrespective of tillage system, and seemed to be greater in low-yielding environments. In a 36-year 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 years) 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 were shown to improve over the years when following winter wheat, whereas yields following grain sorghum remained stagnant (Schlegel et al., 2018). In a 16-year study in Pennsylvania, inclusion of 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.

3.5 Neutral or negative impacts of wheat on other crops

There are cases reported in literature in which including wheat into the cropping system did not benefit other crops. For example, an 8 site-year study in Ohio, USA, reported that including winter wheat in a maize-soybean rotation only increased soybean yields in 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 crop emergence on 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 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.

Wesley et al. (1991) found that soybean had greater yield under mono-cropping (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, since 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, varying also 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 experience increased risk of freeze events during grain fill (Egli and Hatfield, 2014; Seifert and Lobell, 2015). High yielding wheat is usually harvested later than low yielding fields due to a prolonged grain fill period (e.g., Lollato and 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 would decrease ca. 13 kg ha^{-1}, which likely 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 and Cox, 1998a), and Illinois, USA (Behnke et al., 2018), there was no 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 in comparison to continuous soybean in a 15-year study in Ontario, Canada, but under conventional tillage maize yielded better under 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. These findings have important implications for farmers and agricultural policymakers and provide evidence-based recommendations for sustainable crop rotations.

4. 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), 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). Rotating a cool season crop with a warm-season crop such as maize, soybean, or grain sorghum, can enhance the utilization of both summer precipitation and snow accumulation and therefore improve the use efficiency of land, water, and radiation usage, and to cycle nutrients (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 (Hansen et al., 2012; Nielsen et al., 2002). In this section we discuss how wheat presents an opportunity to enhance resource use efficiency.

4.1 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. In North Dakota, Krupinsky et al. (2006) found that spring wheat depleted only 5.9 cm of soil water. 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 by Black et al. (1981) in eastern Montana, 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} (Lollato et al., 2017; Sadras and Angus, 2006) 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, in particular as it relates to protein or lipid concentrations (Sinclair and de Wit, 1975). Additionally, the relatively high water use efficiency of wheat in reference to summer crops may be partially explained by the timing of occurrence of the critical period 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 crop water demand. Although there is some variation for potential water use efficiency of wheat 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 and Angus, 2006).

In a temperate arid zone of northwest China, with 150 mm average annual rainfall and under irrigation, Yin et al. (2015) suggested 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 and Hulugalle, 2006). In Ontario, Canada, Renwick et al.

(2021) observed that adding a cycle of wheat to a maize-soybean no-tillage rotation improved the drought tolerance of maize, primarily 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% as compared to cultivated residue before planting (Cutforth and McConkey, 1997; see Section 5.1).

Precipitation use efficiency and PA 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 and 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, USA, 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 US.

Dryland cropping systems of the US 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-year study by Schlegel et al. (2017) on the semiarid High Plains of Kansas, USA, found that water productivity, available water at planting, and soil water accumulation for grain sorghum were all greater during the fallow period after winter wheat as compared to continuous grain sorghum; available soil water at a depth of 0–180 cm in the soil profile averaged ca. 34 mm more at planting due to off-season accumulation. Grain sorghum yields in this experiment were positively related to available soil water at planting, and grain yields were ca. 4 Mg ha^{-1} or more when available soil water was greater than 250 mm at 180 cm depth, with 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 soil moisture before planting. Subsequently, Schlegel et al. (2019a) suggested that summer crops (grain sorghum, maize, and sunflower) had greater available water at planting, and better crop water productivity, water use, and off-season soil water accumulation when they followed winter wheat vs another summer crop.

4.2 Nutrient use efficiency

Crop rotations can affect nutrient use efficiency directly, 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 and Diaz, 2014). At the other extreme, a successful previous crop can deplete the soil profile, 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, a number of studies have evaluated the effects of wheat on nutrient use efficiency in various cropping systems.

Including wheat in a maize-soybean rotation can enhance yield stability and decrease the N required to maximize maize yields, at least partly due to N rhizodeposition from wheat (i.e., N excretion from living plant roots) as demonstrated by Deen et al. (2016). Similarly, two long-term experiments in Canada found increased mineralizable N when wheat was incorporated into a maize-soybean rotation, compared to a rotation lacking wheat (Congreves et al., 2015). Furthermore, evidence suggests that significant soil organic carbon (SOC) increases in response to N fertilization only occur 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%, returning as much as 4 Mg C ha^{-1} to the soil (Fig. 4). Inclusion of wheat in a rotation can improve N use efficiency in maize and reduce the need for inorganic N fertilizer (Gaudin et al., 2015a). Taveira et al. (2020) found that 30% of N recovered in 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 10–80 kg N ha^{-1} that can be slowly mineralized and made available on the longer term (Fig. 4). Beyond this direct N return in the

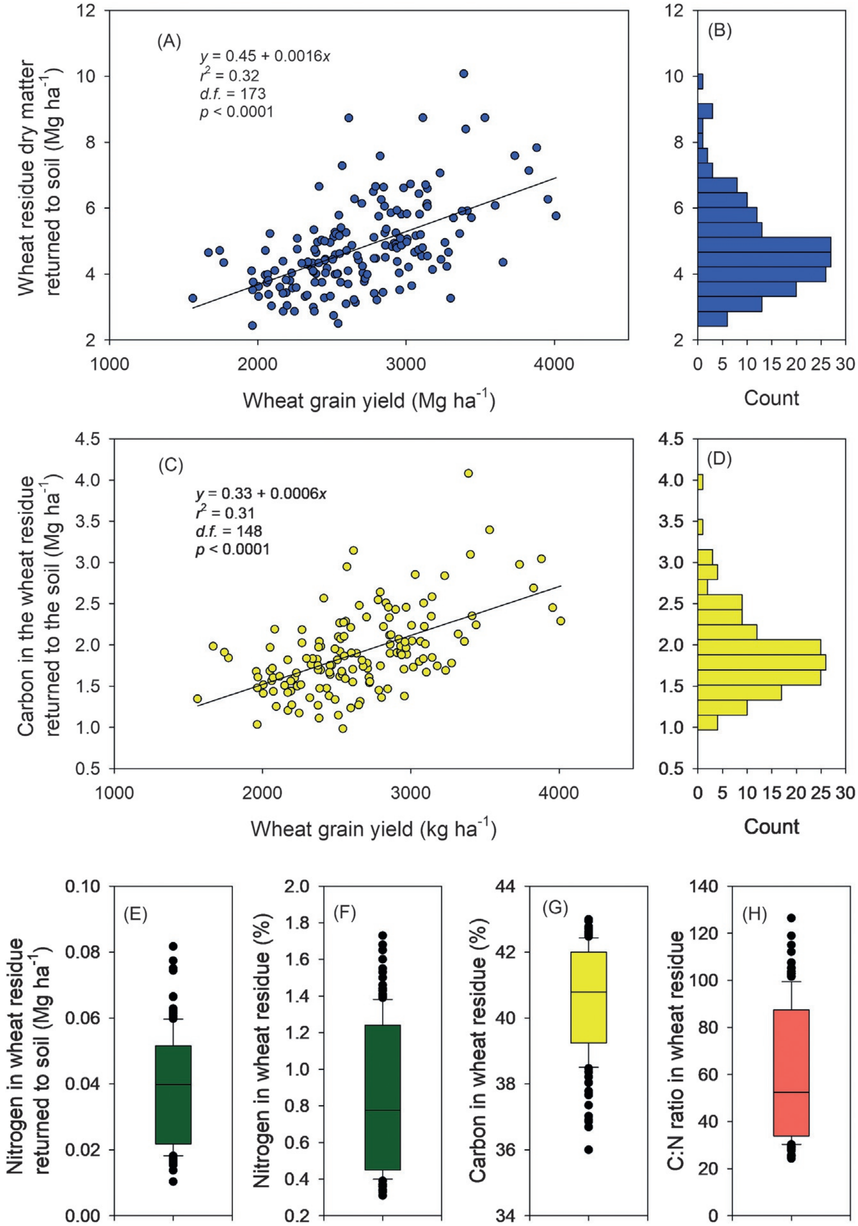

Fig. 4 Wheat residue amount and composition across (A and B) 174 and a data subset of (C–H) 149 wheat crops in Kansas. Amount of (A and B) wheat residue, (C and D) carbon in the wheat residue, and (E) nitrogen in the wheat residue returned to the soil after wheat harvest as (A and C) function of harvested wheat grain yield. In 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. Percent (F) nitrogen and (G) carbon, and (H) carbon-to-nitrogen ratio (C:N) in wheat residue. Percent carbon percent in the wheat residue ranged only in 1.2-fold, whereas the range in nitrogen percent in wheat residue was 5.6-fold. The range in C:N ratio reflected that of nitrogen percent (i.e., 5.2-fold). For details about data collection and processing, please refer to Bott et al. (2023).

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 at 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-year period, which represented 82% of belowground N.

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-year study in Illinois, Zuber et al. (2015) observed greater total N at 60 cm soil depth in a 3-year maize-soybean-wheat rotation compared to a 2-year 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-year rotation compared to the 2-year rotation (343 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, which serves to accelerate microbial activity (Agomoh et al., 2020). Increased potassium use efficiency and potassium recycling also has been observed in cropping system where maize and soybean were rotated with small grains, including wheat (Ambrosini et al., 2022).

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 10–25 cm) compared to a row crop planter (typically 45–90 cm), to distribute P more evenly across the area. 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 may require broadcast application of high P_2O_5 rates to avoid seed damage (Freiling et al., 2022; Randall and Hoeft, 1988). 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 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).

5. Wheat residue management for agronomic and ecological benefits

Wheat produces a significant amount of residue with a high C:N ratio, covering the soil and providing various agronomic and ecological benefits (summarized and compared among residue management programs in Fig. 5). Wheat residue 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, while protecting soil structure from the direct impact of rain drops, thus diminishing runoff and erosion, whether by water or wind. These benefits are reviewed in the next sections.

5.1 Residue for soil water conservation

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. This may be partially explained by reduced soil water evaporation, which wheat residue can lower by 4–25% compared to bare soil as biomass increases from 2.5 to 10 t ha^{-1} (Gava et al., 2013). The effectiveness of wheat residue on soil water conservation is a product of the number of stems m^{-2},

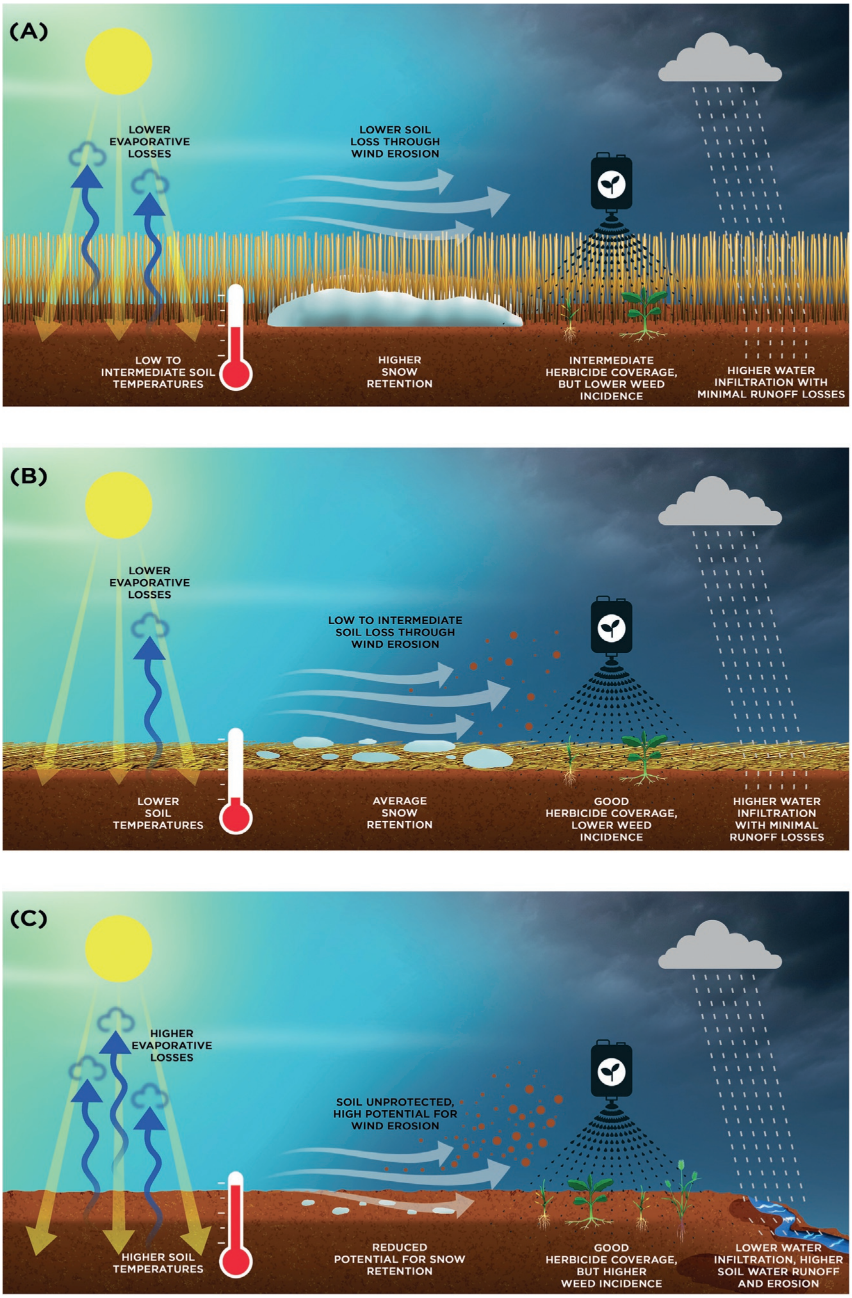

Fig. 5 Schematic representation of wheat residue management implications for soil, wind and water erosion control, soil temperature, soil water infiltration, snow trapping, herbicide spray deposition, and weed incidence with (A) standing wheat residue, (B) flat wheat residue, and (C) no wheat residue.

stem diameter, and stem height (Fryrear and Bilbro, 1994; McMaster et al., 2000). Thus, wheat residue management should focus on maximizing the number of stems m^{-2}, achieved either via plant population or tillering (Bastos et al., 2020), and residue stem height post-harvest, since 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 vs 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. 5A and B; Fryrear and Bilbro, 1994; Van de Ven et al., 1989; Woodruff et al., 1972).

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 soil water evaporation was reduced up to 60% by standing wheat residue, although the reduction was environment-specific. Standing crop residue may allow for 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 virtue of better soil insolation (Bristow, 1988). Higher soil temperature can be beneficial in temperate no-tillage systems where low soil temperatures can delay germination and affect stand establishment (Pittelkow et al., 2015; Unger and Stewart, 1976). Black and 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 0–60 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 (25–36 cm) and short (15–18 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, USA, Schillinger and Wuest (2021) observed that medium wheat stubble height (25 cm) conserved more soil water at the end of the fallow period (14 vs 8 mm, respectively) than tall stubble (75 cm) 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, USA, 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. 6; Black and Siddoway, 1977; Hoefer et al., 1981; Nielsen, 1998). Maximum snow retention capacity is impacted by stalk height, diameter, and soil surface area occupied by stalk (Tabler and Smith, 1986); consequently, due to its density (stems per area), wheat straw has greater snow-catching capacity than that of sunflower, maize, canola, buckwheat, millet, *Panicum miliaceum* L., or sorghum (Merrill et al., 2007). Wheat

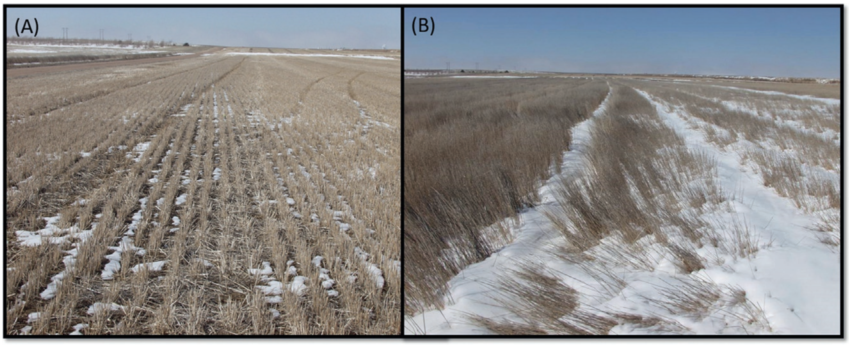

Fig. 6 Snow trapping potential of different winter wheat residue architectures. (A) Flat wheat residue, which results from harvesting the wheat crop using a conventional combine header with low or medium height positioning, has lower potential to retain snow than (B) standing wheat residue, which results 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 stubble that is 15–19 cm, or 30–35 cm, can accumulate two and four times more snow, respectively, than bare soil (Aase and 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 as compared to 15–20 cm tall. Ries and Power (1981) suggested that for each 25.4 mm increase in stubble height, overwinter water storage increased in 6 mm due to greater snow trapping in North Dakota, USA. Although Black and Siddoway (1977) observed similar amounts of snow trapped by 28 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, which translated into greater soil moisture and subsequent maize yield (Hoefer et al., 1981). The capacity of wheat straw to retain snow during winter fallow seems to be independent of wheat variety straw strength, as long as the straw remains standing through the winter (Simão et al., 2021).

5.2 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 and 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 and Allison, 1976). Some evidence suggests that ~110 standing wheat stems m^{-1} can reduce soil loss due to wind erosion by ca. 73% (Pi et al., 2020). Wheat stubble 15–19 cm tall can reduce wind passage 1.5-fold compared to bare soil at 9 cm above ground level, whereas stubble 30–35 cm tall can reduce it five-fold (Aase and Siddoway, 1980). The greater effectiveness of standing wheat residue to control wind erosion than flat residue results from its greater absorption of the wind's energy, raising the zero-velocity-point above the soil (Bilbro and 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. 5).

The use of wheat residue as a mulch can also reduce soil 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 compared to soybean residue when an equivalent amount of biomass was present, and wheat residue was better at mitigating water erosion given an equivalent 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 as compared to a tilled area within the same field (Fig. 7; Lollato et al., 2012). Wheat residue has also mitigated water erosion better than corn residue, given similar amounts of residue on the soil surface (Cogo, 1981; Laflen et al., 1981; Lopes et al., 1987; Wischmeier and 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 (60–180 mm h^{-1}), and soil types (silt loam, clay loam, loam). Wheat crops can produce as much as ~10 t ha^{-1} of residue (Fig. 4), offering an unparallel opportunity for erosion control as it increases in parallel with wheat residue (Rahma et al., 2019).

Overall, wheat stubble height of 25–45 cm provides a similar degree of soil moisture conservation (Black and Siddoway, 1977; Cutforth and McConkey, 1997; Schillinger and Wuest, 2021; Schlegel et al., 2023), wind erosion control (Fryrear and Bilbro, 1994), snow trapping (Aase and Siddoway, 1980; Black and Siddoway, 1977), and herbicide spray deposition on the soil (Simão et al., 2020) when compared to stubble heights >45 cm. Although standing wheat residue is beneficial in temperate environments due to better snow trapping and increased solar irradiation of the soil surface,

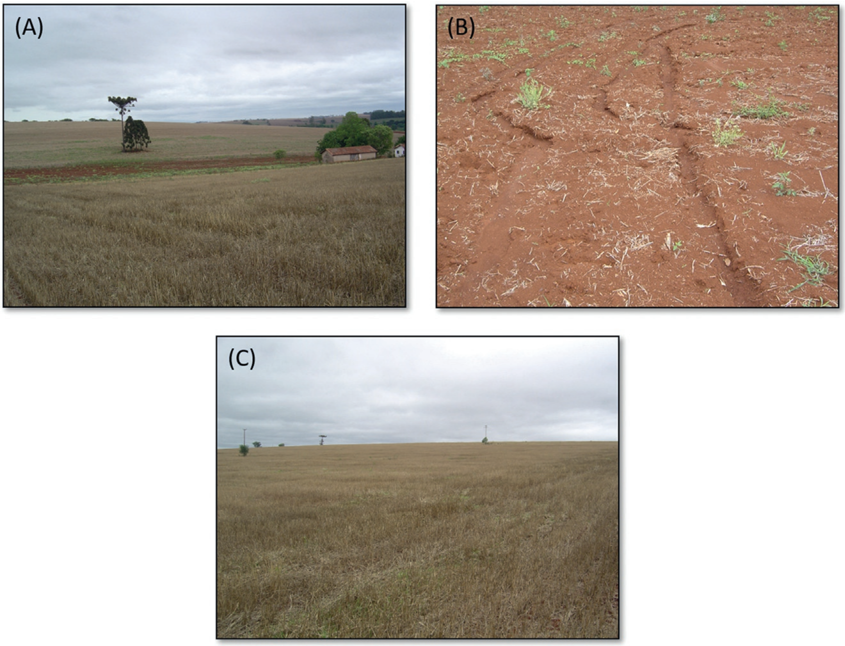

Fig. 7 Soil erosion prevention due to wheat residue in an Oxisol in a commercial farming operation in the subtropical climate of southern Brazil. (A) Distance photo of a small area where the soil was tilled to correct soil ruts from combine harvesting as compared to the remaining operation under no-till 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. For more details, please refer to Lollato et al. (2012). *Photo credit and approval for publication: Dr. Romulo Lollato.*

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.

5.3 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.

The inclusion of winter cereals in systems dominated by spring-annual rotations can reduce weed density and the system's herbicide requirements (Beres et al., 2010b). This is especially true in seasons when winter cereals have a 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., 2010b). The competitive ability of the crop against weeds can be enhanced by in-season decisions that modify wheat's 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., 2010a; Blackshaw, 1994; Thomas et al., 1993). For example, Li et al. (2019b) 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 as 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-year maize-soybean-wheat rotation than after soybean in a 2-year 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 that 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 the inclusion of 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; Dhanda 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: 24–126; Fig. 4), coupled with large amount of biomass returned to the soil, can prolong these benefits in comparison to residues of other crops with lower C:N ratios, as 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 (Aslam et al., 2017; Jilani et al., 2008; 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). 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 and 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., 2000a).

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 micro-habitat 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 as 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

Table 1 List of 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 and Entz (2009)
Cassia obtusifolia L.	Sicklepod	5%	Steinsiek et al. (1982)
Digitaria ciliaris (Retz.) Koeler	Southern crabgrass	10%	Li et al. (2019a)
Echinochloa crus-galli 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.)	Omitted-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. (2000b)
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 and Entz (2009)
Sida spinosa	Prickly sida	10%	Blum et al. (2002)

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 (*A. 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 herbicide reached the soil surface when 2250 kg ha^{-1} of flat wheat residue was present (Banks and Robinson, 1982). When targeting the soil surface, both standing and flat residue orientations can intercept similar amounts of herbicide. However, if the target is the weed canopy, flat residue is preferable. 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 0–60 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.

5.4 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 and Kantrud, 1987; Lokemoen and 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 and Parshad, 2011). For example, ring-necked pheasant (*Phasianus colchicus*), the most important upland fame 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, USA, with nest density averaging 6–8 nests per 100 hectares (Duebbert and 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 and 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 and Parasharya, 2018).

6. Soil

It can take up to 18 months for 80% of wheat residue to be mineralized in the field, and our data shown in Fig. 4 supports previous findings that C returned to the soil can average 5.4 Mg ha^{-1} $year^{-1}$ for ca. 11 Mg ha^{-1} of residue (Buyanovsky and 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 and Wagner, 1988). A high C:N ratio of ca. 82 (though with a large variability driven by plant nitrogen status; Fig. 4) contributes to the slow decomposition rate of wheat residue (Truong and 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 and 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.

6.1 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 (Congreves et al., 2017; Gaudin et al., 2015b). A 15-year study in Illinois, USA, compared soil properties of continuous maize, continuous soybean, a 2-year maize-soybean rotation, and a 3-year maize-soybean-wheat rotation and found that the 3-year rotation including wheat resulted in the greatest water aggregate stability (0.87 kg kg^{-1}), whereas continuous soybean and the 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-year 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 conducted 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 and Zentner, 1993). In a 27-year study in eastern Kansas, USA, 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-year soybean-grain sorghum rotation (Doyle et al., 2004). Later, in the same experiment, Fabrizzi et al. (2007) found that after 29 years, the highest 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-year soybean-sorghum rotation under conventional tillage practices. SOC fractions in cotton systems, in particular lighter fractions, are 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 and 29 years 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-year periods, Van Eerd et al. (2014) demonstrated that indices of soil quality at 0–15 cm depth (i.e., total N, SOC, aggregate stability, and penetrometer resistance) increased with frequency of winter wheat in the rotation, consistent with the findings of Andrews et al. (2004). In a 15-year 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. Lower soil compaction, as indicated by decreased soil bulk density, was also observed when one cycle of wheat 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 and 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, compared to legumes (Hulugalle and Scott, 2008).

6.2 Soil microorganisms

Maize-based rotations under reduced tillage in a sandy loam soil in Michigan, USA, had the greatest mega-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. Quantity of soil bacteria were 1.4 times greater when winter wheat interseeded with red clover was included in a maize-soybean rotation, although 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-year 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).

6.3 Soil carbon sequestration and greenhouse gases 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 (0.20–0.33 $kg\,CO_2\,kg^{-1}$ grain) (Gan et al., 2011). Wheat may even act as a C sink in certain cropping systems; 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. 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., 2006b).

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. For example, Gan et al. (2011) concluded that spring wheat can act as a sink of CO_2 (ca. 0.03–0.4 kg CO_2 eq. 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. Afterwards, 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 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 ploughing and zero tillage in China. Even with 50% wheat straw removal under conventional tillage, a single wheat cycle in a 4-year maize-maize-soybean-soybean rotation sequestered more SOC (23.9 vs 21.4 g kg $soil^{-1}$) and total yearly C inputs (3190 vs 3002 kg C ha^{-1} $year^{-1}$) than a maize-maize-soybean-soybean rotation in a 37-year study in Elora, Canada, with more pronounced benefits when wheat was interseeded with red clover (King et al., 2020; Meyer-Aurich et al., 2006b). 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-year study in China, a maize plus wheat relay system had a 17.3% lower C footprint compared to monocrop maize (4022 vs 4747 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 vs a maize-soybean-wheat rotation in a study in Illinois, USA (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 and Blesh, 2018), its lower N requirement may still help mitigate climate change due to lower N_2O emission during the wheat growing season (Bronson and Mosier, 1993). Irrigated maize had greater N_2O emissions and less CH_4 fixation than either dryland or irrigated winter wheat in northeast Colorado, USA, regardless of N management (Bronson and Mosier, 1993). In a no-tillage dryland system on sandy clay loam soil in eastern South Dakota, USA, Lehman and Osborne (2013) found that a 4-year maize-field peas-winter wheat–soybean rotation acted as a C sink, whereas a 2-year rotation of maize-soybean was a source of greenhouses gases. In this study, the 4-year rotation accrued 596 kg C ha^{-1} $year^{-1}$ in the top 30 cm of soil, while the 2-year rotation lost 120 kg C ha^{-1} $year^{-1}$. Later in the same study, Lehman et al. (2017) observed that daily N_2O emissions were 24% lower in the 4-year rotation than in the 2-year rotation (2.3 vs 3.0 g N_2O ha^{-1} day^{-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-year rotation (Buyanovsky and Wagner, 1987).

In Australia, rotations including wheat, have improved cotton yield, mitigated the declining of 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 (Jarecki 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, inclusion of 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.

7. Benefits of wheat in mitigating biotic stresses

7.1 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 and 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/pests 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 allow for 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 (USA) study, although the effectiveness of this approach was inferred to depend heavily on the susceptibility of the soybean cultivar to SCN (Long and 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 and 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 as the microbial communities can produce antimicrobial compounds or compete for resources (Bastian et al., 2009; 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 5–57% (Kutcher et al., 2013).

Wheat rotations have also been evaluated for control of white mold, *Sclerotinia sclerotiorum*, in soybean and canola. Gracia-Garza 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 and Novakowiski, 2017; Garza et al., 2002; 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 and 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., 2006, 2007). A 5-year 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 depend 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 and Baldwin, 2002). 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 (Lv 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, USA, 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 and Mazzola, 2003; Mazzola and 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.

7.2 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 and 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., Qureshi and Michaud, 2005; Tauber and 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, as 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, USA, 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 and 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 and 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., Colares et al., 2015; Lopez and Teetes, 1976; Prasifka et al., 1999; Rice and Wilde, 1988).

8. 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 (Singh et al., 2021; Zacharias and Grube, 1984). 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 and 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 and 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 since 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 (Fieser et al., 2006; Moore, 2009; Redmon et al., 1996; Taylor et al., 2010). Studies in Oklahoma, USA, 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 and 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 in which 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, USA (Katsvairo and Cox, 2000a; Singer and Cox, 1998b), New Jersey, USA (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 (Singh et al., 2021; Zacharias and Grube, 1984). However, Janovicek et al. (2021) showed that adding winter wheat to a maize-soybean rotation every 4–5 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. (2006a) observed that a maize-soybean-wheat rotation consistently provided the higher and more stable net returns (by \$30–\$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, USA, 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, USA, double-cropped soybean-wheat rotations can yield higher net return per unit of irrigation water when monocrop soybean does not cover production costs (Wesley and 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 and 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).

9. 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—many of which are specific to wheat—and explain 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 yield and decrease yield variability of other crops in a rotation. In less complex cropping systems, the addition 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 some recent evidence suggests that 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 incorporation of 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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Conflict of interest

The authors declare no conflict of interest.

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