

Sustainable intensification of crop production: Reviewing current knowledge and investigating opportunities for bread with lower global warming potential

by

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Abstract

The move toward sustainable crop production has brought attention to environmental issues; meanwhile, the growing population pressures the food system to increase production. Sustainable intensification addresses both issues by intensifying management to increase production while still being environmentally sound; however, definitions and quantifications of sustainability have been inconsistent and subjective. Therefore, this thesis attempted to provide clarity about sustainable intensification of crop production following two major strategies: (i) a comprehensive literature review of current knowledge across major crops, and (ii) a field and laboratory study to inform decision making in bread wheat systems. In our first effort, we conducted a review of sustainability literature to identify commonalities in definitions, themes, and indicators across the production, environmental, economic, social, and human condition domains of sustainability. We also reviewed metrics and tools commonly used in sustainability studies, including those applicable to research and those relevant at the farm level. In addition, current sustainability literature representing four of the major food crops [wheat, *Triticum aestivum* L.; rice, *Oryza sativa* L.; maize, *Zea mays* L.; and soybeans, *Glycine max* (L.) Merrill] was investigated to identify common topics and research gaps. A majority of these studies addressed production and environmental or economic indicators of sustainability, with fewer studies delving into human or social aspects. Translation of research findings to field applications (i.e., the adoption of sustainable practices and technologies by producers) seem to be limited by adoption initial cost (not only direct monetary but also in terms of human capital) and unavailability. There seems to be opportunities for future research to include end-use quality parameters in sustainability assessments and to increase the robustness of small-scale assessments of social and human condition sustainability. In our second effort, we established

field experiments where we replicated the management intensities currently adopted in commercial wheat fields to identify avenues to increase bread production and improve or maintain environmental footprints simultaneously. Four management intensities (i.e., low, average, high, and top) were derived from a survey of 656 commercial fields and replicated in trials conducted in 23 site-year combinations in the sub-humid and semi-arid regions of Kansas. Milling and baking analysis provided quality data to the loaf of bread. Cradle-to-grave life cycle assessment (LCA) quantified global warming potential (GWP) and energy inputs relative to a functional unit of 1 kg of bread, while estimates of carbon sequestration and bread energy output allowed the calculation of net GWP and net energy yield (NEY). As management intensity increased, both grain yield and protein increased despite a negative relationship between the two within management intensity. The combination of yield and protein gains resulted in higher bread yields. GWP and energy inputs for both the wheat production phase and the entire bread production system increased as a result of added inputs with each step of intensity, but the magnitude of increase when yield-scaled was alleviated by increases in bread yield. Although mean GWP and energy input increased with more intensive management (1.22-1.46 kg-CO₂e and 15.02-16.34 MJ per kg-bread⁻¹), differences decreased as bread yield increased, which was further reduced when net GWP and NEY were considered. These results suggest an opportunity to increase bread yields with minor increases in environmental impact per unit bread.

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Chapter 1 - Sustainable intensification of crop production: A review of current knowledge and future prospects

Abstract

The move toward sustainable crop production has brought attention to environmental issues; meanwhile, the growing population pressures the food system to increase production. Sustainable intensification addresses both issues by intensifying management to increase production while still being environmentally sound; however, definitions and quantifications of sustainability have been inconsistent and subjective. Therefore, we conducted a review of sustainability literature to identify commonalities in definitions, themes, and indicators across the production, environmental, economic, social, and human condition domains of sustainability. We also reviewed metrics and tools commonly used in sustainability studies, including those applicable to research and those relevant at the farm level. In addition, current sustainability literature representing four of the major food crops [wheat, *Triticum aestivum* L.; rice, *Oryza sativa* L.; maize, *Zea mays* L.; and soybeans, *Glycine max* (L.) Merrill] was investigated to identify common topics and research gaps. A majority of these studies addressed production and environmental or economic indicators of sustainability, with fewer studies delving into human or social aspects. Many of these studies highlighted management modulations as opportunities to improve a system's sustainability, especially in the production and environmental domains. Translation of research findings to field applications (i.e., the adoption of sustainable practices and technologies by producers) seem to be limited by adoption initial cost (not only direct monetary but also in terms of human capital) and unavailability. There are opportunities for future research to include end-use quality parameters in sustainability assessments and to

increase the robustness of small-scale assessments of social and human condition sustainability. Here, we took an initial step in reviewing the current knowledge around sustainable intensification to provide directions at all levels including farms, supply chains, industry programs, and policy.

1.1 Introduction

Crop production must increase by 50% by 2050 to meet the food demands of a growing population (Parry & Hawkesford, 2010). Global food security is further challenged by a changing climate and geo-political conflicts, which call for improvements in the climatic and economic resilience of local, regional, and national food systems (Al-Saidi, 2023; Barrett, 2013; Junior et al 2022). Feeding the world without massive cropland expansion requires increases in grain yield (Foley et al., 2005), which can be attained through crop intensification and the adoption of intensified management practices to narrow existing yield gaps (van Ittersum et al., 2013). However, it is critical that these efforts to increase yield avoid excessive input usage that would lead to negative socio-economic and environmental impacts, such as increased global warming potential and decreased profit (Greer et al., 2020).

The need for more food production while adapting to climate change and reducing environmental footprint has increased public concern and is now impacting consumers' food choices, which led many multinational companies to develop sustainable sourcing programs for agricultural commodities (Appendix A) (Leach et al., 2016; Thomson et al., 2017). However, very few studies have provided frameworks backed by scientific evidence for measuring progress in sustainable intensification of crop production (e.g., Barnes and Thompson, 2014; Gadanakis et al., 2015; Mouratiadou et al., 2021). Thus, while these existing individual private sourcing programs may be valuable, they are fragmented and therefore inefficient, bombarding

producers with different initiatives that require labor- and resource intensive- data collection and may not always be backed up by scientific evidence. Thus, we propose that advancing the science of sustainable intensification of crop production is essential to improve policy and to ensure that these private programs are not only relevant to the consumer, but also result in real advances toward sustainable food production, helping to address the gap between science and action (Clark & Harley, 2020; Wyborn et al., 2019).

There is a consensus that sustainable yield increases to meet growing food demands must (i) be profitable, (ii) supply produce that meet expectations for human consumption, and (iii) account for social prospects, while (iv) attaining acceptable standards of environmental quality (Cassman, 1999; Sadras et al. 2009). Therefore, the proper assessment of the benefits and challenges of any component of a given agricultural system must be performed in the context of multiple specific and quantitative production, economic, environmental, social, and human consumption indicators (Smith et al., 2017). However, the literature on sustainable intensification is currently fragmented, challenging the quantification of sustainability using the most appropriate metrics (Smith et al., 2017). To address this gap, here we review the history of sustainability research, the existing concepts and metrics of sustainable intensification of crop production, and finally we consider previous studies in wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.), and soybeans (*Glycine max* (L.) Merrill) as examples to summarize the current literature and identify gaps for future research. We focused on these four crops because together they account, directly or indirectly, for about 41 and 37% of total human calories and protein consumption (FAO, 2020) and are an integral part of modern, globalized food systems that are structured for products that can be dried quickly, stored for long periods, easily transported, and processed with fairly low energy requirements for food consumption

(Cassman and Grassini, 2022). We acknowledge, but deliberately avoid the inclusion of legumes in African agriculture, of integration of break crops into continuous crops, of smallholder systems, of agro-ecology, of biotechnology, and of the concomitant addition of animal or tree production to grain crops (i.e., silvopastoral systems) to a system's sustainability as these have been the focus of previous reviews (Broom, 2017; Chianu et al., 2011; Das et al., 2023; Ewert et al., 2023; Franke et al., 2018; Hegewald et al., 2018; Kirkegaard et al., 2008; Popoola et al., 2022; Reich et al., 2021; Seymour et al., 2012; Smith et al., 2017; Vanlauwe et al., 2019). We attempt to provide some clarity in explaining the large variability in methods used to quantify, and in the reported outcomes from, interventions for sustainable crop intensification, while considering the depth and breadth of each. We also make recommendations of potential mechanisms to extend these insights to the farm level so that sustainability programs are relevant across the supply chain.

1.2 Definitions of sustainability: Historical perspective and agronomic context

Sustainability is a widely discussed subject that lacks an agreed-upon definition, as these have been developed tailoring the needs of individual disciplines. Still, having a clear definition of sustainability is crucial to prioritizing actions and policies (Brown et al., 1987). In simple terms, the idea of 'sustainability' can be expressed as the ability of a system to persist into the future (Costanza & Patten, 1995; Hansen & Jones, 1996). This suggests a degree of uncertainty present when considering how the system will affect the future, which cannot be directly observed (Hansen & Jones, 1996). Because of this, most definitions of sustainability refer to what actions one predicts will result in sustainability (Costanza & Patten, 1995). This brings challenges defining sustainability in a consistent manner.

The term ‘sustainability’ is often referred to as ‘sustainable development’ within many fields of study. Sustainable development was first defined in the famous “Brundtland Report” published in 1987 by the United Nations as “...development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). The report further explained that sustainable development is a process where changes are made considering the needs of both the present and the future, rather than a fixed state that can be achieved. This approach is consistent with the definition approved by the Food and Agriculture Organization (FAO) of the United Nations in 1988 that describes sustainability as meeting present and future generation’s needs through changes in management, conservation, and institution (FAO, 1989). These definitions of sustainable development led to the creation of 17 goals by the United Nations in 2015, which called for global efforts to better conditions for humanity and the planet (United Nations, 2015). The goals address human well-being, economic growth, and improvement of ecosystems in a sustainable manner, while acknowledging the requirement of global support.

Other definitions of sustainable development outline similar themes as those in political documentation. Sustainability has been considered a methodology for strengthening the social and environmental systems of the planet whose support systems are becoming threatened (Basiago, 1995). However, a system that is environmentally sound but does not produce enough economic reward cannot be considered sustainable (Yunlong & Smit, 1994). Therefore, the development of society should follow natural processes while also being economically responsible (Glavič & Lukman, 2007). From a global perspective, countries that are “achieving higher and more equally distributed well-being levels within ecological limits” are considered to be developing sustainably (S. Zhang & Zhu, 2020). From these definitions arise common

concepts; thus, sustainable development is often grouped into three pillars regarding economic, environmental, and social aspects (Khan, 1995; Muralikrishna & Manickam, 2017). The classic visual of these pillars is often portrayed in the form of a Venn diagram (Mebratu, 1998).

In the scope of agriculture, the concepts of sustainability follow a similar structure. All ecosystems that are impacted either directly or indirectly by agriculture must be considered for crop production to be sustainable (Lewandowski et al., 1999). The integration of natural processes and the reduced usage of finite resources with adverse impact the ecosystem are crucial in sustainable production agriculture (Pretty, 1997, 2008), with some authors further emphasizing the conservation of land from degradation while being practical economically and socially acceptable (Brown et al., 1987).

Several agricultural organizations in the United States have developed their own definitions for sustainable agriculture. The American Society of Agronomy (ASA) defines sustainable agriculture as “growing adequate nutritious and affordable food for the world’s growing population while protecting the environment” (ASA, 2022). The United States Department of Agriculture (USDA) has a similar definition, also emphasizing sufficient income for farmers and other individuals in the sector (USDA, 2022). Other organizations like the American Farm Bureau Federation focus mostly on environmental issues and promote “climate-smart” production practices (American Farm Bureau Federation, 2022). Most definitions of sustainable agriculture revolve around the same three principles of economic, environmental, and social sustainability; however, some studies and frameworks include additional domains. A review of farm-level sustainability assessments identified five domains used in the literature evaluating agricultural sustainability, including: environment, governance and institutional, social, economic, and agronomic (Chopin et al., 2021). Similar to this agronomic grouping, other

literature reviewing agricultural sustainability shows several articles proposing “productivity” as an attribute to be considered in assessments (Rao & Rogers, 2006). Food security and human nutrition are also discussed in several studies (Eakin et al., 2017; Herforth et al., 2014; Mazac et al., 2021), which are sometimes placed in a “human” or “human condition” domain (Musumba et al., 2017; Smith et al., 2017). Here, we review the five principles of economic, environmental, social, production, and human sustainability within the scope of agriculture.

1.3 Metrics for quantifying sustainability in agricultural systems

1.3.1 Economic

The introduction of economic sustainability as a topic of interest can be attributed in part due to the 1980s farm crisis that occurred in the United States. Growing demand for U.S. grain increased commodity prices in the 1970s, making investments in land favorable and paying back large farm debts feasible. Increases in land and equipment prices in the 1980s, along with decreasing commodity prices due to high quantities of production and falling exports, placed a great financial burden on farmers. These events brought forward discussion of policy change and concerns that the system was not financially sustainable. The problems experienced in the 1970s and 1980s showed how reliance on very few crops as an income source and spending too much on inputs to produce these crops can create economic issues for farmers (Schaller, 1993).

Economics has been commonly considered in most decisions made within the agricultural sector. While profitability tends to be the most often highlighted metric, economic sustainability encompasses factors that affect longevity and decisions that farms make. On a micro-scale, it is defined as the ability of a farm or system to survive in fluctuating economic conditions over time (Latruffe et al., 2016). This can include topics on the ability to withstand variations in profit, diversifying income across entities, and requirements of labor. Economic

sustainability should also be considered on a macro scale such as general welfare, which can be determined through poverty indicators. Markets are large determinants of producers' decisions; therefore, the development of markets plays a large role in economic sustainability.

Within this context, the most common metrics used to evaluate the economic sustainability of a given agricultural system are provided in Table 1.1, including the system's profitability, variability of profit, financial capital, and resilience.

1.3.2 Environmental

Environmental sustainability has been one of the main focuses in the development of sustainable agricultural practices due to the pressing need to adjust practices in the context of climate change. Some authors argue that the other pillars cannot be achieved unless ecological factors are satisfactory (Lewandowski et al., 1999; Morelli, 2011), as the improvement of human welfare by protecting resources and preventing harm to the environment is the center of sustainability (Goodland, 1995). Environmental sustainability focuses on ecosystems and the functions that support life for humans (Dong & Hauschild, 2017), including the preservation of these ecosystems while meeting current and future human needs (Morelli, 2011). Themes in environmental sustainability literature, as categorized by Morelli (2011), include meeting societal needs, preserving biodiversity, regeneration of natural resources, recycling and reuse, and limitations on nonrenewable resources and waste production.

Decisions in the agricultural sector have a direct impact on the environment; thus, environmental sustainability is crucial for an overall system's long-term sustainability. The most common metrics used to quantify a system's sustainability – from the environmental perspective – are shown in Table 1.2. The agricultural sector plays a significant role in greenhouse gas (GHG) emissions (Garnett, 2011), which in turn impacts climate change. The sector is

responsible for 21% of all GHG emissions, including 14% of carbon dioxide emissions, 41% of methane emissions, and 69% of nitrous oxide emissions (Shukla & Skea, 2022), creating pressure on agriculture to reduce emissions. Due to the resources used and the emissions associated with its production, energy consumption is often considered in environmental sustainability (Chel & Kaushik, 2011; Omer, 2008). Nitrogen losses from fertilizer use in agricultural soils can cause nitrous oxide emissions (Van Groenigen et al., 2010), in addition to contaminating groundwater and eutrophication (Zhang et al., 2015). Soil phosphorus in eroded agricultural soils has also been linked to eutrophication of water bodies (Bennett et al., 2001), which has several negative effects including declines in aquatic species through promotion of algal blooms (Daniel et al., 1998; V. H. Smith & Schindler, 2009). In addition to its effects on eutrophication, soil erosion also causes the negative effects of land degradation through loss of topsoil (Lairez et al., 2023). Monoculture agriculture has influenced ecosystem biodiversity, which can also have positive effects in pest management (Pacini et al., 2003). Additionally, pesticide use can have potential issues with toxicities and unintended consequences with non-target organisms (Margni et al., 2002).

1.3.3 Social

Due to its subjective nature, social sustainability has very limited literature on the quantification metrics compared to the environmental and economic pillars (van Calker et al., 2007). The current available metrics for social sustainability are shown in Table 1.3. Social sustainability includes aspects from both the survival and happiness of the human life (Brown et al., 1987). One of the most common themes in literature is the concept of equity, which refers to equality among people of different backgrounds and justice regarding all three pillars of sustainability (Eizenberg & Jabareen, 2017; Jabareen, 2008; Littig & Griessler, 2005; McKenzie,

2004). Meanwhile, the lack of equity has a role in degradation of the environment, as addressing equity and other basic human needs allows people to begin considering ecological concerns (Vallance et al., 2011). Additionally, safety or security emphasize human health and the right to protection when vulnerable (Colantonio, 2009; Eizenberg & Jabareen, 2017). Human rights and work conditions are often used to evaluate quality of life and societal impacts but are not enough to evaluate social sustainability (Janker & Mann, 2018). Other themes relate to happiness, employment, access to resources, and quality of life (Colantonio, 2009; Littig & Griessler, 2005). The evaluation of social sustainability should not be confined to a specific scale, as social sustainability involves matters on the farm, community, and society levels in agriculture (Latruffe et al., 2016).

1.3.4 Productivity

With a growing global population and limited land available, especially under the need to reduce the expansion rates of agricultural land into native vegetation and when rates of crop productivity have plateaued in many important food growing regions of the world (Grassini et al., 2013), increases in production on current agricultural land are necessary (Foley et al., 2005). Therefore, productivity (and its gap in reference to the potential productivity, i.e., yield gap; van Ittersum et al., 2013) is often considered in sustainability assessments (Table 1.4). Productivity refers to the ability of a system to generate outputs (Rao & Rogers, 2006). Intensifying production on land currently devoted to agriculture is a way to maintain adequate food supply. The concept of sustainable intensification is based on this idea of increase yield per unit land while being economically- and environmentally-cognoscenti and is one approach to make agriculture more sustainable (Oberč & Schnell, 2020). This concept involves increasing food production on existing farmland without causing more damage to natural resources. This also

calls for an increase in efficiency of production, as well as the entire food system (Garnett et al., 2013). Yield-gaps are one of the most widely used methods for quantifying sustainable intensification potential and productivity (e.g., Silva et al., 2021; Yuan et al., 2021; 2022), as this displays the difference between actual and attainable yields (Mueller et al., 2012). Within sustainability, productivity accounts for the ability to reach optimum yields while balancing other aspects of sustainability such as economics and environmental targets.

1.3.5 Human Condition

The sustainability principle of human condition focuses on concepts related to human health, food quality, security, and safety (Table 1.5). Food quality centers on having access to food that meets human dietary needs (Herforth et al., 2014). In addition to access to nutritional food, the production of nutrient-rich foods and crops is of global importance. This is especially true for those nutrients considered to be micronutrients by crops (Graham, 2008). Food security can be related to nutrition in the sense of having access to an adequate amount of food and to nutritious food (Eakin et al., 2017). Food safety is not often included in sustainability assessments; however, existing literature has identified it as a gap within sustainability frameworks (A. Smith et al., 2017). This can include topics on pesticide residues (Carvalho, 2006), risks of mycotoxins (Wagacha & Muthomi, 2008), and other food contamination factors that can negatively affect human health.

1.4 Tools to assess a system's sustainability

Assessments of sustainability are very complex due to their multidisciplinary nature, thus creating challenges when evaluating whether assessment methods are suitable for a given situation. To address these challenges, the Bellagio Principles for Assessment were created as a guide for sustainability assessments in 1996 (Hardi & Zdan, 1997) and later updated to become

known as BellagioSTAMP (Sustainability Assessment and Measurement Principles) (Pintér et al., 2012). The revised principles provide common principles by which assessments should follow regarding its vision, considerations, scope, framework and indicators, transparency, communication, participation, continuity, and capacity. Using the principles of BellagioSTAMP, literature has developed a comprehensive methodology that provides procedural steps for sustainability assessment that define the sustainability approach, targets, the context in which decisions are made, and the methodologies used in the assessment (Sala et al., 2015). Although these themes are general in nature, they have direct application to production agriculture by providing guidance for thorough sustainability assessments.

Some early literature provides a procedure for farmers to insure sustainable crop production, with a focus on environmental preservation (Lewandowski et al., 1999). The first steps include recognizing compounds emitted and released from crop production and identifying the impact to the ecosystem that they have. Indicators of the ecosystem are selected to describe the state of the ecosystem, and threshold values are determined for these indicators. By tracing these back to the farm level, tolerable levels of emissions and releases are determined to create indicators. Management practices crucial to sustainable crop production are identified with thresholds for farm inputs to create indicators for evaluation. Farms can then be evaluated for the level of sustainable crop production based on these farm-level indicators.

Defining “sustainability” in different contexts is crucial to the determination of indicators and metrics to be used in its evaluation (Huang et al., 2015). These indicators are context-dependent for the specific topic of interest (Dong & Hauschild, 2017). It is important to identify the most applicable indicators due to the surplus of possible metrics that could be tied to sustainability (Verma & Raghubanshi, 2018). Similarly, the benefits of monitoring an indicator

should be higher than the costs, making it necessary to place a valuation on conceptual benefits like a higher understanding for future decision-making (Pannell & Glenn, 2000). Tools that evaluate and combine these indicators are useful for comparative and comprehensible assessments of sustainability.

Many tools are available for farm-level assessment of sustainability. Although most sustainability tools share a similar purpose, there is a high level of variation between methods of assessment (de Olde et al., 2017). In this sense, assessment tools are better equipped to help direct change on a specific farm or production system, rather than changing agriculture as a whole (Slätmo et al., 2017). The adoption of sustainable practices is dependent on farmers and these tools are becoming more directive towards farmers (Coteur et al., 2020). Here, we discuss sustainability tools that can be used in both research and commercial farm settings.

1.4.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a tool that can be used to quantitatively evaluate the potential environmental impacts of a product over its life cycle (Lee & Inaba, 2004). These measurements start at the manufacturing, packaging, and transportation of the raw materials used in input creation (often referred to as “cradle”), and its assessment can stop at any stage within the production of a given product (for example, a LCA of agricultural crops can stop at the product produced in the farm [often referred to as “gate”; e.g., (Biswas et al., 2010; Grassini et al., 2012; Taki et al., 2018; L. Zhang et al., 2021)]); or it can evaluate the entire production, consumption, and disposal of the end product [often referred to as “grave”; e.g. (Deng et al., 2021)]). LCA focuses primarily on the environmental aspects and usually does not consider economic and social properties of the systems evaluated. It considers the products produced, emissions to the environment, and other environmental impacts. An LCA consists of four phases:

i) goal and scope definition, ii) inventory analysis, iii) impact assessment, and iv) interpretation (Lee & Inaba, 2004).

The first phase of LCA involves defining the *goal and scope* of the assessment, which identifies the purpose, boundaries, assumptions, and the products resulting from the study. The LCA's goal recognizes the product in question and the target audience and is where the objective of the study is located. This determination lays out the reasoning for completing the analysis. The scope focuses on the specifics of the assessment including methods for the impact assessment, data quality requirements, the functional unit, and the boundaries and parameters used in data collection.

In the second phase, the life cycle *inventory analysis* (LCI) includes quantifying the material and energy inputs and outputs for the product through data collection and calculations. This can occur through public databases, literature, or direct measurements. These are the basis for the life cycle *impact assessment* (LCIA). This third phase of an LCA consists of four elements which are used to estimate potential environmental impacts: i) classification, ii) characterization (these are considered mandatory to the assessment), iii) normalization, and iv) weighting (these are considered optional). Based on the impact they may have on the environment, LCIA inputs and outputs are classified into categories. These inventory parameters are then quantified within their respective impact categories and is characterized by equivalency factor for comparison. Normalization can be conducted to account for the period of time and the geography of the product being assessed. These values may also be subjected to weighting, where a relative significance is assigned to each of the impact categories.

LCI and LCIA results are analyzed in the final phase as the life cycle interpretation, which comprises of three elements: i) identification of key issues, ii) evaluation, and iii)

conclusions. Key issues that have a substantial effect on the overall impact of a system should be identified and are crucial for improving the product's environmental impact. All results should also be evaluated for their completeness, sensitivity, and uncertainty, and whether they were completed consistently with quality data. Finally, conclusions and recommendations may be made concerning the evaluated data and key issues.

Life cycle assessment has been used to analyze the environmental effects in several areas within agriculture, especially within the major agronomic crops of the world - many of which are summarized in Section 5. Briefly, in rice production, LCA has been used to estimate greenhouse gas emissions (Abdul Rahman et al., 2019; Gathorne-Hardy, 2013) and combinations of environmental factors such as carbon sequestration, water provisioning, air quality and water quality (Liu et al., 2020). Rice management strategies and tactics have been compared using LCA, including conventional versus organic production (He et al., 2018; Jirapornvaree et al., 2021), planting and input tactics (Habibi et al., 2019), and residue management (Soam et al., 2017; Van Hung et al., 2020). Other studies analyzed rice production systems as a whole to identify problematic environmental impacts (Jimmy et al., 2017; Wang et al., 2010). Wheat production LCA studies featured freshwater pesticide contamination impacts (Berthoud et al., 2011), greenhouse gas emissions in organic and conventional systems (Meisterling et al., 2009), energy use estimations (Houshyar & Grundmann, 2017; Taghavifar & Mardani, 2015), and fertilizer quantity comparisons (Charles et al., 2006). Comprehensive assessments of production are featured specifically for wheat (Holka, 2016) and for small grains in general (Fallahpour et al., 2012).

1.4.2 Water-Energy-Food Nexus (WEF)

The Water-Energy-Food Nexus (WEF) is a concept developed by the Food and Agriculture Organization of the United Nations (FAO) in 2011 (FAO, 2014). WEF was developed as another outlook to address the issue of sustainability in the context of using limited resources to provide for human needs. It focuses on the interaction of water, energy, and food to assess the impact on the sector in question, as well as other sectors that may be affected in this regard. This is especially directed towards use by governments and large multinational companies to assess the impact of policy changes and address the management of resources as they relate to the sustainable development goals created by FAO.

The WEF Nexus Index has been developed to quantify the interactions between the pillars of water, energy, and food (Simpson et al., 2022), which are valued equally within the framework. Each pillar has two sub-pillars which address equitable access and physical availability. A total of 21 indicators are used to characterize and quantify these sub-pillars. Water access is characterized by the percentage of people using basic drinking water and sanitation services, as well as implementation of Integrated Water Resources Management [part of a Sustainable Development Goal (United Nations, 2015)]. Water availability includes annual freshwater withdrawals, renewable freshwater resources, environmental flow requirements, and precipitation. Energy access is highlighted by electricity access, renewable energy consumption and output, and carbon dioxide emissions. Consumption of electricity and energy imports are used to describe energy availability. Food access is characterized by malnourishment, children affected by wasting, children who are stunted, and adult obesity. Indicators of food availability include protein supply, grain yield, adequacy of dietary energy supply, and value of production. After the determination of indicator values, normalization transforms them to a uniform scale.

Scores are then calculated at the sub-pillar level by using the mean of indicators, and equal weighting is used at the pillar level to ensure each pillar is represented with equal importance. Finally, the average of the pillars determines the overall WEF Nexus Index.

The WEF Nexus Index is intended to be used on a large scale and a national index has been calculated for 181 countries (Simpson et al., 2022), in addition to implementation in several different disciplines including agriculture. WEF concepts are found within many studies and WEF Nexus Index has been used to evaluate production agriculture, especially when comparing crop species and cropping systems. Seven crop species were compared using this method in Iran (Saray et al., 2022), 14 crop species also in Iran (Sadeghi et al., 2020), four species in China (Feng et al., 2022), and seven different cropping systems in China (Li et al., 2021).

1.4.3 Response-Inducing Sustainability Evaluation (RISE)

Farm-level sustainability can be quantified using “Response-Inducing Sustainability Evaluation”, also known as RISE (Hani et al., 2003). RISE aims to simplify sustainability assessment, accounting for the aspects of environmental, economic, and social sustainability on the entire farm. This model uses 12 indicators and evaluates them based on an estimate of the pressure the indicator places on the farming system and the actual measurement of the indicator in the system. Ecological indicators include energy, water, soil, biodiversity, emission potential, plant protection, and wastes/residues. Cash flow, farm income, investments, and the local economy indicate economic sustainability. The social system of the entire farm (i.e., worker compensation, family worker, and employee relationships) is evaluated as the last indicator. Because it is intended for use at the farm level, boundaries are set at one year temporally and are limited to the farm area spatially.

RISE also includes two different viewpoints of sustainability to determine a degree of sustainability (DS) for each indicator. These viewpoints are the “driving force” (i.e., the pressure on sustainability) and “state” (i.e., the current situation’s effects on sustainability) of the indicator. These are rated on a 0-100 scale using local or regional comparisons, which allows for normalization of each indicator. The DS of each indicator is plotted in a polygon for visualization and interpretation. Additionally, other dimensions investigating stability, the farmer’s actions, energy, and animal welfare are assessed to supplement the polygon visualization.

The RISE method of sustainability assessment inputs actual farm data and is in the context of regional data, making it the most relevant tool for farmers (de Olde et al., 2016). In Poland, it was used in the comparison of organic versus low-input conventional farming (Berbec et al., 2018). Another study on organic farms within the vegetable, dairy, pig, and poultry sectors in Denmark used RISE for sustainability assessments (de Olde et al., 2016).

1.4.4 Sustainability Assessment of Food and Agriculture Systems (SAFA)

Sustainability Assessment of Food and Agriculture Systems (SAFA) was developed by the FAO intending to create a sustainability assessment framework for global use (FAO, 2014). This framework is intended for a diverse audience, including all entities associated with agricultural value chains and is applicable for government reference. Four dimensions of sustainability are used to distinguish the systems evaluated with SAFA including governance, environment, economics, and social impact. Sustainable governance considers topics in corporate ethics, accountability, participation, rule of law, and holistic management as they relate to decision-making and implementation. The category of environmental integrity focuses on minimizing negative ecological impacts to maintain essential systems using themes of the

atmosphere, water, land, biodiversity, materials and energy, and animal welfare. The economic dimension focuses on resilience rather than development, focusing on investments, vulnerability, product quality, and the local economy. Social sustainability in the context of SAFA includes fulfilling human needs without compromising others; and social well-being is measured following topics of decent livelihood, fair trading practices, labor rights, equity, human health and safety, and cultural diversity.

Following the four dimensions of sustainability defined in the SAFA guidelines, procedures follow a four-phase structure: i) mapping, ii) contextualization, iii) indicators, and iv) reporting. The mapping phase describes the entity being assessed while defining boundaries, exclusions, and external relationships of the entity. Under the context of the objectives and boundaries, the sub-themes associated with each dimension and indicators are reviewed for relevance. Indicators are selected, calculated, and thus weighted so that each sub-theme has equal weight in the final rating. Procedures and results are documented in the performance report, where they are visualized and reviewed for quality, credibility, and transparency. To further facilitate the use of SAFA, FAO has developed an open-access software for easier implementation of the SAFA guidelines (FAO, 2014).

SAFA has been used as a tool in livestock systems, specifically for beef production in Sicily and Indonesia (Cammarata et al., 2021; Gayatri et al., 2016). In production agriculture, it has been implemented in banana (*Musa* spp.) production in Ecuador (Bonisoli et al., 2019), coffee (*Coffea canephora* and *Coffea arabica*) production in Uganda (Ssebunya et al., 2017), and organic crop production in the United Arab Emirates and Italy (Shamsi et al., 2019).

1.4.5 Indicateurs de Durabilite des Exploitations Agricoles (IDEA)

Another tool to assess farm-level sustainability is *Indicateurs de Durabilité des Exploitations Agricoles*, otherwise known as the IDEA method (Zahm et al., 2008). This method, translated as “Farm Sustainability Indicators,” was first developed in 2000 (Boisset et al., 2008) and has since been updated to its fourth version named IDEA4 (Zahm et al., 2022). From a conceptual standpoint, IDEA4 evaluates a farm’s territorial effects, self-sufficiency, long-term potential, resilience to variation, and global responsibility. The framework assesses sustainability within the three dimensions of environmental, economic, and social sustainability using 13 components. In the environmental dimension, the components considered are diversity, material and energy flows, resource use restraint, favorable production conditions, and the reduction of environment and human health impacts. The economic dimension is comprised of financial viability, independence, transferability, and efficiency. In the social dimension has components including food supply, local economy and development, employment and work quality, and ethics. These components categorize the 53 indicators used to assess sustainability through IDEA.

IDEA methodology has been implemented to assess sustainability in animal agriculture, including dual-purpose cattle farms in Mexico (Salas-Reyes et al., 2015), beef cattle farms in Tunisia (Mhamdi et al., 2017), sheep farms in Algeria (Benidir et al., 2013), and dairy farms in Mexico (Fadul-Pacheco et al., 2013). Production agriculture has utilized IDEA for irrigated cereal crops of Algeria (Chaouch et al., 2021), rubber farms in Thailand (Biret et al., 2019), maize production in Mexico (Paulino-Flores et al., 2017), and diverse farms in Morocco (Baccar et al., 2019).

1.4.6 Public Good (PG)

Developed in the United Kingdom, the Public Good (PG) Tool is used to assess the sustainability of a farm based on effects to goods that are generally non-rival and non-excludable (Gerrard et al., 2012). The public goods included in the assessment include soil management, biodiversity, landscape and heritage, water management, manure management and nutrients, energy and carbon, food security, agricultural systems diversity, social capital, farm business reliance, and animal health and welfare. Each good is assessed by activities involving questions that are scored between one and five (five representing the most benefit). The PG tool was released in 2012 as an excel spreadsheet intending to be accessible to farmers and easy to utilize.

Few applications within literature using the PG tool exist in agriculture. In Europe, PG was used to assess the sustainability of agroforestry systems (Smith et al., 2022). In animal agriculture, European countries were evaluated and compared for the sustainability of goat and sheep farms (Paraskevopoulou et al., 2020).

1.4.7 Comparisons of benefits and drawbacks of different sustainability tools

Due to the subjective nature of sustainability science, the tools that have been developed to evaluate a system's sustainability have strengths and weaknesses depending upon the contexts in which they are used. Compared with other methods of assessment, RISE has a focus on the environment, SAFA has an emphasis on social sustainability, and PG focuses on the environmental and economic domains (Alaoui et al., 2022). In a study of 15 prevalent methods, SAFA seemed to provide an optimum balance between analysis completeness with reasonable expenditure of resources (Bonisoli et al., 2018). In a study of Swedish farmers, RISE had the most potential to evaluate the social sustainability of farmers compared to the SAFA and IDEA methods (Röös et al., 2019). In a review of 19 farm-level tools, SAFA and RISE were among the

most consistent with BellagioSTAMP (Arulnathan et al., 2020). Out of 48 tools, SAFA, RISE, PG, and IDEA were deemed the most applicable in assessing the sustainability of Danish farms, with RISE being the most relevant according to farmers (de Olde et al., 2016). Additionally, some studies combined multiple assessment methods to diversify the measurements, to refine the study, or to provide measurements to be implemented within a different framework. For example, WEF was complemented by LCA metrics to assess tillage and irrigation effects on wheat and maize production sustainability (Zhang et al., 2022). The very nature of sustainability assessments results in each method having its advantages and disadvantages. Nonetheless, this review provides enough background so that researchers, practitioners, and industry can select the method (or methods) that best fit their needs based on the systems being evaluated.

1.5 Distribution of sustainability studies by crop

Many studies on agricultural sustainability focused on individual crops and how management of those crops can affect sustainability. Numerous crops are grown worldwide, but four crops are dominant in terms of the area they cover annually, and of the fraction of calories and protein provided directly or indirectly for human consumption. According to FAO statistics, the agricultural crops that covered the most area in 2021 were wheat, maize, rice, and soybean, occupying over 125 million hectares (FAO, 2021). These crops are also directly responsible for 41% and 37% of the total human calories and protein intake globally (FAO, 2020).

Google Scholar was searched to find published scientific articles relating to sustainability and sustainable production practices relating to these important food crops. Terms used in the search included different key words relating to sustainability and its domains, such as: sustainability, sustainable, conservation, environmental, ecological, LCA, energy, greenhouse gases, climate change, social, economic, productivity, human, and quality. These were paired

with the four food crops (wheat, maize, rice, and soybean) individually for each search inquiry, and relevant articles were compiled. Of the 137 papers compiled, 109 were conducted in a single country whose distribution by crop are displayed in Figure 1.1. The articles were categorized based on their topic within sustainability and the distribution of these topics by crop are shown in Figure 1.2.

1.5.1 Wheat

A number of studies used comprehensive methodologies to quantify the sustainability of wheat production, summarized in Table 1.6. For example, LCA was used in many studies regarding nitrogen fertility (Goucher et al., 2017; Keikha et al., 2023; Masuda, 2016; Zhang et al., 2021), as well as cropping systems (Shrestha et al., 2020; Xu et al., 2022), residue management (Ingrao et al., 2021), irrigation (Taki et al., 2018), organic production (Verdi et al., 2022), and general assessments of system's sustainability (Deng et al., 2021; Ghasemi-Mobtaker et al., 2020). Other comprehensive work on wheat sustainability includes the use of WEF methodology (Fabiani et al., 2020), case studies (Chatelin et al., 2007; Fischer et al., 2022; Zhao et al., 2019), field studies (Mayer et al., 2015), and surveys (Mustafa et al., 2021). Additionally, major sustainability issues in durum wheat (*Triticum turgidum* L. ssp. *durum*) have been the subject of previous reviews (Zingale et al., 2022).

Beyond these comprehensive assessments of wheat sustainability, a number of studies investigated individual aspects of system's sustainability using wheat as case studies. For example, some previous environmental work used LCA to investigate GHG emissions from different residue managements (Monteleone et al., 2015), to identify emission hotspots in wheat production (Biswas et al., 2010), and to study the impact of plant breeding and genetics on emissions (Riedesel et al., 2022). Other GHG emission work used modeling to quantify regional

emissions (Shi et al., 2021) and field studies to compare nitrous oxide emissions from various management tactics (Wang et al., 2022). Energy usage of wheat production was also explored in comparison of other food sources (Avlani & Chancellor, 1977) and in different areas of wheat production (Safa & Samarasinghe, 2011).

Previous work also revolved around soil factors including soil quality and fertility. Many of these focused on residue management, including retention of crop residue (Bakht et al., 2009; Ghimire et al., 2015; Liu et al., 2022), planting into living mulch (Carof et al., 2007), production under saline soil conditions (Miransari & Smith, 2019), and organic and inorganic fertilizer effects on soil health (Imran et al., 2021; Kang et al., 2005). Soil fertility research within the context of sustainability included the effects of organic matter additions on phosphorus losses (Zhang et al., 2017), nutrient use efficiencies for wheat cultivars (Salim & Raza, 2020), and a review of current nutrient knowledge in wheat production (Panhwar et al., 2019). In addition, the benefits of variable rate technology on environmental and economic factors have been explored (Fabiani et al., 2020). Grain quality aspects of sustainability – which fall within the human domain of sustainable intensification – focused on crop management impacts on milling and baking strategies to improve end products (Cappelli & Cini, 2021) and the effects of mycotoxin-infested grains (Cheli et al., 2013).

While comprehensive sustainability assessments are common among wheat studies, residue management is an area lacking in sustainability studies. Residue is considered in some soil quality studies, but not often in the context of erosion prevention. In addition, studies on sustainable intensification and the adoption of sustainable practices are lacking. Although some studies have been conducted on grain quality, additional work could help with understanding sustainability factors downstream in the product chain. Other potential research could include

pest management and biodiversity, which are other topics missing from wheat sustainability studies.

1.5.2 Maize

Several studies quantified the sustainability of maize grain production using comprehensive frameworks, including many examples using LCA methodology and others (Table 1.7). These ranged from full comprehensive assessments of farmers' practices (Grassini et al., 2012) to specific topics such as nitrogen fertilizer management (Sadeghi et al., 2018; Yao et al., 2021), stover management (Kim et al., 2009), and tillage practices (Król-Badziak et al., 2021). Regional assessments of sustainability incorporate LCA (Boone et al., 2016; Giusti et al., 2022) and a review of LCAs of maize grain production on the national level (Kim et al., 2014). Other comprehensive work assessed the sustainability of maize production using case studies (Lairez et al., 2023) and technology adoption (Jones-Garcia & Krishna, 2021).

Studies on specific environmental factors or management practices are common in maize production. The effects of maize production induced air pollution on human health were explored (Hill et al., 2019), as well as energy and emissions of maize agroecosystems (Yousefi et al., 2014). Residue management research focuses on the removal of maize stover following harvest of the grain, including the harvest of maize stover for various uses (Adler et al., 2015; Karlen et al., 2011), burning stover (Tiammee & Likasiri, 2020), and destruction due to tillage (Afshar & Dekamin, 2022). Other literature explores the positive and negative effects of retaining residue, including managing for lower soil temperatures and nitrogen immobilization for the succeeding crop (Kong, 2014). Sustainable nitrogen management studies are often related to emissions and losses, including the effects of genotype and rates (Kim & Dale, 2008), the use of nitrogen balance as a predictor for nitrate losses (Tamagno et al., 2022), and in-season rate

determination using chlorophyll measurements (J. Zhang et al., 2007). Other studies evaluate the contribution of organic fertilizer inputs to soil quality versus inorganic fertilizers (S. Huang et al., 2010).

Other themes addressed in maize sustainability literature related to the use of genetic modification (GM) technology include insect resistance to the Bt gene (Glaser & Matten, 2003), consumer decisions on GM products (Aerni et al., 2011), and the economic and environmental impacts of GM maize production (Brookes & Dinh, 2021). In addition, seed quality in low input environments was investigated (Geus et al., 2008).

Maize sustainability studies cover residue and fertility management, but lack in other areas such as pest management and soil quality. In addition, water management studies are also missing from a crop that is heavily irrigated in some parts of the world. Grain quality is assessed from the seed production standpoint; however, other studies on end use quality could improve sustainability literature. Overall increases in maize sustainability studies could be beneficial, as there were only 24 total found in this study.

1.5.3 Rice

Recent literature in rice sustainability is perhaps the most abundant among crops, focusing mostly on environmental impacts of rice production (Table 1.8). Comprehensive assessments of sustainability used several different methods. LCA studies assessing several impact categories were conducted to compare specific practices such as residue management (Soam et al., 2017), to identify environmental impact hotspots in rice production (Giuliana et al., 2022), and to evaluate rice production on a national level (Liu et al., 2020). Meanwhile, inconsistencies and gaps in these LCA studies are identified in a review of 72 rice LCAs (Ahmad et al., 2023). Numerous other studies assessed the sustainability of rice production around the

world using other methods, including studies in Thailand (Mungkung et al., 2022; Stuart et al., 2018), Vietnam (Stuart et al., 2018), India (Devkota et al., 2020), Bangladesh (Roy et al., 2014), the continent of Asia (Devkota et al., 2019), and several global studies (Mishra et al., 2022; Nawaz et al., 2022; Yuan et al., 2021). In addition, intensification of rice production systems was explored in Uruguay (Pittelkow et al., 2016; Tseng et al., 2020). Studies on farmer adoption of sustainable practices address the most adopted practices (Connor et al., 2021), factors influencing adoption (Ashoori et al., 2017), and ways adoption can be increased (Rahman & Bulbul, 2015).

Numerous studies have been conducted on individual aspects of sustainable rice production, including the quantification of GHG emissions. LCA is often applied in these studies to specifically explore global warming potential, highlighting organic production systems (Jirapornvaree et al., 2021; Nunes et al., 2016), intensive production systems (Brodt et al., 2014), and hotspot analysis (Rahman et al., 2019). Another large focus of rice sustainability research is in the area of residue management. While residue removal through burning is common practice in rice production, effective management or utilizing straw for alternative uses are tactics that can be more ecologically friendly (Kumar et al., 2022). Studies are centered around retaining or incorporating the crop's residue (Kumar et al., 2020; J. Zhang et al., 2021) and utilizing a green manure crop in conjunction (Li et al., 2019; Zhou et al., 2020). Several studies evaluated the impacts of alternative uses for rice straw from a systems outlook, including mushroom production (Nguyen-Van-Hung et al., 2019), biofuel (Sharma et al., 2020), and bioenergy (Harun et al., 2022; Singh et al., 2021). Soil quality indicators for different soil orders have been discussed (Biswas et al., 2017), as well as the effects of perennial rice on soil quality parameters (Zhang et al., 2023).

Fertility management studies have focused on reducing the environmental impacts by optimizing fertilizer inputs while incorporating residue with green manure (Zhuang et al., 2022), optimizing nitrogen applications (Liang et al., 2017; Yu et al., 2014), and utilizing best management practices to maximize sustainability and nutrient efficiency (Fageria et al., 2003). GHG emissions have been explored in relation to different irrigation strategies (Miniotti et al., 2016; Moreno-García et al., 2021). Positive effects of biodiversity on ecological sustainability were observed in paddy rice systems (Luo et al., 2014), with the incorporation of a legume crop in the rotation (Gautam et al., 2021), and with fish farming integration (Berg et al., 2017). Diversity also has an effect on pest management (He et al., 2019), which relates to biological pest control (Fahad et al., 2021) and other non-chemical pest control methods (Hong-Xing et al., 2017). In addition, a sustainable framework for pest management in rice has been discussed (Savary et al., 2012).

Other topics within rice sustainability reside in the human domain, within the areas of grain quality and grain nutrient content. Rice grain quality parameters have been investigated using organic fertilizers (Zhou et al., 2022) and irrigation strategies (Ishfaq et al., 2021), in addition to managing arsenic accumulation from groundwater irrigation (Upadhyay et al., 2020). Biofortification has received much attention to address human nutrient deficiencies, which can best be achieved through genetics and fertility (Sheoran et al., 2022). Zinc deficiencies can be addressed with the application of zinc fertilizers (Bana et al., 2022) paired with genetic promotion of grain zinc content (Peramaiyan et al., 2022). Genetic engineering has also been a recent theme in biofortification of iron, zinc, and β -carotene (Majumder et al., 2019), especially in the case of Golden Rice (Dubock, 2017). Additionally, consumer preference of sustainably produced rice was assessed in Vietnam (Connor et al., 2022; My et al., 2018) and Nigeria

(Okpiaifo et al., 2020), while the acceptability of rice produced in the United States explored in Thailand and Japan (Aoki et al., 2017).

Likely the most complete of the four crops in terms of sustainability assessment, comprehensive assessments are a much smaller proportion of total studies for rice as compared to the other crops. Other research gaps might include evaluations of energy use or net energy or the development of sustainable technologies. In addition, more studies on water management and greenhouse gas emissions could improve recommendations for flooded rice.

1.5.4 Soybean

Sustainability assessments on soybean production are much rarer than the other crops discussed, especially in the context of social sustainability (Jia et al., 2020) (Table 1.9). Comprehensive studies investigated the three dimensions of economic, environmental, and social sustainability through LCA (Zortea et al., 2018) while other methods looked into the effects of genetically modified soybeans on overall system's sustainability (Phélinas & Choumert, 2017). Multi-indicator environmental studies emphasized the effects of transportation through LCA (da Silva et al., 2010; Dalgaard et al., 2008; Knudsen et al., 2010) and explored the effects of intensive management through other methodology (Greer et al., 2020). LCA identified residue and fertilizer input management as hotspots for GHG emissions (Mohammadi et al., 2013; Raucci et al., 2015), which were also explored in field studies (Langeroodi et al., 2019). Comprehensive field (Andrade et al., 2022) and modeling (Balboa et al., 2019) studies have explored economic, human, and production aspects of adopting an improved management package in commercial soybean fields across the US. Micronutrient response in soybeans (Thapa et al., 2021) as well as tillage and irrigation for sustainable rotation options in rice systems (Giacomeli et al., 2021) were studied in the topic of soil management. Sustainable pest

management is another popular subject in soybean management, addressing the combined use of tools to manage soybean aphids (Hodgson et al., 2012; Ragsdale et al., 2011), cultural control methods for sudden death syndrome (Rodriguez et al., 2021), and integrated pest management (Bueno et al., 2021). Other subjects within sustainable soybean management explored yield-gaps in Brazil (Sentelhas et al., 2015) as well as the opportunities to avoid deforestation of Amazon Forest through soybean intensification (Marin et al., 2022). Harvest and storage methods have also been evaluated for grain quality preservation (Coradi et al., 2020). Challenges in sustainable management of soybean supply chains have been reviewed (Jia et al., 2020), and specifically have focused on non-GMO soybean supply chains (Teuscher et al., 2006).

Sustainability studies for soybeans are the most scarce of the four crops totaling 19 in this study, indicating several areas for improvement. Very few studies look at soil factors, especially in terms of fertility and residue management. Social sustainability is also lacking in topics such as sustainability adoption and consumer preference. In addition, as a crop deeply involved with genetic modification, few soybean studies consider its effects on sustainability. Furthermore, few studies consider end use quality, biodiversity, and water management.

1.6 Potential for crop-specific management modulation on sustainability

Negative effects on sustainability indices that are independent of human control such as short-term climate or weather variables have little opportunity for regulation. Crop management, however, often influences various aspects of sustainability, and therefore presents the opportunity to modulate sustainability. Although agronomic management differs between crops, similar themes are expressed amongst prospects for positive sustainability impacts.

The most frequent opportunities for management modulation of sustainability of crop production perhaps are found within the environmental domain. Surface residue management is

beneficial in erosion prevention (Turmel et al., 2015) which preserves topsoil that is critical to maintaining long-term productivity (Larson et al., 1983). Surface residues also positively influence factors such as organic carbon, nutrient, and water content in the soil (Bakht et al., 2009; Ghimire et al., 2015; Karlen et al., 2011; Kong, 2014; Liu et al., 2022; Zhang et al., 2021). This is especially important when managing eutrophication due to runoff, as surface protection has been shown to reduce phosphorus losses (Zhang et al., 2017). Losses of nitrogen can be reduced while still maintaining yield by optimizing fertilizer rates and timing of application with various residue practices (Kim & Dale, 2008; Liang et al., 2017; Lollato et al., 2021; Pittelkow et al., 2013; Sadeghi et al., 2018; Yu et al., 2014; Zhuang et al., 2022). These losses can come in the form of leaching (Tamagno et al., 2022) or through emission of nitrous oxide (Wang et al., 2022). Residue management also plays a role in GHG emissions (Kumar et al., 2020; Langeroodi et al., 2019; Nguyen-Van-Hung et al., 2019; Sharma et al., 2020; Tiammee & Likasiri, 2020), providing an opportunity for reductions with proper management. Additionally, increases in sustainability are related to increases in biodiversity (Berg et al., 2017; Gautam et al., 2021; Luo et al., 2014) which can also positively affect pest control (He et al., 2019). Biological and cultural control methods can be effective alternatives or additions to chemical control methods (Fahad et al., 2021; Hong-Xing et al., 2017; Rodriguez et al., 2021), while an integration of methods can lead to more sustainable management (Andrade et al., 2022; Bueno et al., 2021; Hodgson et al., 2012).

Productivity is mainly influenced by using optimal agronomic practices for maximizing yield. Increases in grain yield through intensification of crop management can be large enough to offset per area increases in input usage, resulting in lower global warming potential per unit grain yield produced (Grassini et al., 2012). Controllable yield variability is mainly influenced by

nutrient, pest, and water management, meaning that changes in the management of these can increase productivity (Mueller et al., 2012). In addition, sub-optimal practices in land management, sowing and harvest dates, plant densities, and varietal selection can lead to larger yield-gaps (Zhang et al., 2016), decreasing a systems sustainability. The optimization of these management factors in terms of yield can provide avenues to increase productivity and sustainability of agricultural systems, and it is important to highlight that different farming systems require individual strategies to achieve high yield, sustainable crop production (Silva et al., 2021).

1.7 Considerations of grain quality on sustainability metrics

While maintaining long-term global food security remains one of the biggest goals of sustainability, some argue that the focus should be directed towards providing food of good nutritional value (Campbell et al., 2016; Mustafa et al., 2021). This is especially relevant as the focus on increasing crop grain yield in the last decades has resulted in greater carbohydrate accumulation in cereal grains, reducing the concentration of more nutritious components such as grain protein and macro- and micro-nutrients (Maeoka et al., 2020; Miner et al., 2022) – a scenario that may be accentuated with future increases of CO₂ concentration (Loladze, 2014). We note in passing that this can further accentuate not only micronutrient deficiencies in underdeveloped countries (Zhu et al., 2018) but potentially contribute to the obesity pandemic and associated diabetes and cardiovascular events (Diamond et al., 2020, 2021). Still, grain quality is rarely included in metrics of overall agricultural sustainability, but quality parameters have been explored individually for sustainability purposes. In particular, research on biofortification of rice either through management or genetics has attempted to combat human malnutrition (Bana et al., 2022; Dubock, 2017; Majumder et al., 2019; Peramaiyan et al., 2022;

Sheoran et al., 2022). Other research on factors that affect grain quality includes practices in grain production (Andrade et al., 2022; Cappelli & Cini, 2021; Cruppe et al., 2018; Giordano et al., 2023; Ishfaq et al., 2021; Zhou et al., 2022; Raj et al., 2023; Tian et al., 2022) and post-harvest handling (Cheli et al., 2013), in addition to practices to prevent toxic compounds (Cheli et al., 2013; Upadhyay et al., 2020). Grain quality parameters play a role in human health, productivity, and efficiencies that can relate to environmental factors, making it crucial for overall sustainability assessments especially in a context where the population of underdeveloped countries can be impacted by further impoverishments in grain nutrition, and that of developed countries go through obesity pandemics and associated diseases.

1.8 Practical implications for adoption of sustainable technologies

Despite the increasing popularity of topics surrounding sustainable production of agricultural crops over the last several years, there are still issues with the adoption of sustainable practices in commercial agronomic settings. Overarchingly, the key to overcome the lack of adoption of sustainable practices include (i) implementing policies to make such practices profitable, and (ii) building human capacity through education and Extension so that the intricacies of such practices are well understood. This is especially true in underdeveloped countries with no – or very incipient – Extension systems to educate the general population. Sometimes, constraints associated with the adoption of new agricultural practices that may seem more sustainable can be driven by high additional costs of new technologies and equipment, concomitantly to the need of acquiring specialized skills and the associated time investment to enhance the value embodied in the technology (Griffin et al., 2004, 2016; Miller et al., 2017). For example, the use of active sensors to determine optimal nitrogen rates variable across the field has demonstrated a potential to reduce the amount of N applied while maintaining grain

yield of cereal crops for years under experimental conditions (Arnall et al., 2013; Mullen et al., 2003; Raun et al., 2001; Scharf et al., 2011; Schwalbert et al., 2018), thus suggesting opportunities to be more sustainable in at least two domains (i.e., economic and environmental). Still, the adoption of this technology at large-scale commercial agriculture is still small relative to the adoption of other precision agriculture technologies such as yield monitors, machine guidance, and autosteer (Bramley and Ouzman, 2019; Ofori et al., 2020).

Still from a practical perspective, problems may also arise when technologies are unavailable or unattainable, and influenced by the local markets available to the producer. New herbicides to overcome herbicide tolerant-weeds in no-till or reduced tillage practices are examples of unavailable technologies, thus other practices must be adopted to compensate (Kumar et al., 2020). Crop diversity within rotations are examples of potentially sustainable practices (He et al., 2019) that are strongly influenced by the markets available to producers. Limited access to markets tends to lead to poor adoption of diversification due to lack of economic viability. Most grower's decisions are driven by economics and would therefore be more apt to adopt sustainable practices, such as diversified crop rotations, with policy support and the development of markets (Rodriguez et al., 2021; Song et al., 2021; Wang et al., 2021). Sustainability incentives are still lacking, although some industry companies have recently launched programs assisting the transition to sustainable agriculture (Appendix A).

1.9 Future research, policy development, and public-private partnerships

Studies on environmental sustainability are abundant and relevant. However, other areas of sustainability could be further explored in future research. For example, overarching themes of sustainability are clear (i.e., production, environmental, economic, human, and social), but lack metrics of assessment for some domains especially on small scales. This is particularly true

in the social domain, where many of the themes are well defined, but lack convenient metrics for evaluation. Macro-scale metrics are common, but indicators on the farm-level are scarce. The human condition domain is also lacking in consideration, especially in relation to food quality. In crop production, quality is usually only considered in terms of protein or oil content but often not in the context of sustainability. Other parameters such as the quality of protein and oil, as well as other processing quality parameters are often excluded as well, which could have effects on efficiencies and end-product quality. Along the same lines, nutritional quality should be of concern and warrants inclusion in sustainability metrics for the purposes of human health.

The environmental domain is possibly the most studied and advanced over the last several years, rightfully so being that sustainable intensification may call for an increase of inputs. Nevertheless, restraints on time, labor, and costs cause direct ecological measurements to be difficult. This highlights the need for continuously updated models to accurately estimate environmental indicators in different situations. Still, taking measures to reduce negative environmental effects should not hinder productivity enough to cause concern for economic viability and adequate food supply. Additionally, the current state of climate change should be considered in management and genetic decisions while also working towards its mitigation. Sustainable agriculture has made major advances over the last several years, but still requires further progress to improve the global food system.

Policy formulation has the ability to push agricultural sustainability forward, however policy implementation depends on building human capacity, especially in underdeveloped countries. Farms tend to be economically driven, and therefore do not put other domains as a high priority unless those beneficial practices also result in higher profit. Incentives for producers to use sustainable practices – either as governmental policy or as industry-led programs – could

lead to greater adoption of sustainable practices by offsetting potential profit-loss from such practices. Similarly, premiums for higher quality products could encourage producers to manage at a higher intensity that will create benefits later in the supply chain. Sustainability can be very situation-dependent, and therefore should not be viewed from a blanket approach but rather on a case-by-case basis.

Finally, we see opportunities for public-private collaborations in advancing towards sustainable intensification of crop production, leading to changes in sustainability across the value chain. Private programs have the ability to compensate producers for adoption of sustainable practices, potentially moving the needle at scale. Meanwhile, two challenges are common challenges of programs that compensate growers for the adoption of sustainable practices: (i) the verification of claims related to practice adoption, and (ii) exploration of data so that new recommendations of actual sustainable practices are developed. Advances have been made to utilize satellite imagery to quantify the use of given practices such as conservational tillage (e.g., Azzari et al., 2019), but the adoption of other management aspects of crop production still contribute to the first challenge as they rely on boots on the ground verification by program deployers which is costly and time consuming. Here, and using the U.S. system as an example, private companies could collaborate with Land Grant Universities so that county and district Extension educators contribute with ground truthing claims. The second challenge (the collection of large datasets by private companies) offers opportunities for researchers across disciplines in the public sector (e.g., life cycle assessment specialists, agronomists, computer scientists, grain science specialists, etc.) to collaborate and, through state-of-the-art data science, develop new recommendations regarding sustainable intensification of crop production. This information then could be relayed back to producers and partners across the value chain through

Extension venues and to producers associated with Industry partners to move entire value chains towards more sustainable systems.

1.10 Concluding remarks

Sustainable intensification of crop production is difficult to define and to evaluate due to its specificity to each system; still, it should be high priority in near future policy development and research funding to produce more nutritious food while sustaining or improving environmental indicators. The different domains and themes around the central idea of sustainability challenge progress in this area as positive advances in one domain may be accompanied by tradeoffs in others, highlighting the need for multidisciplinary approaches to move the current global food system to greater sustainability. The reduced number of studies on the human and social domains of agricultural sustainability is concerning and could have contributed to the current status of malnutrition and obesity. The improvement of current, and the development of new assessment tools is crucial to identify practices that increase sustainability to utilize on all scales of agriculture, including specific crops, cropping systems, farms, and supply chains. The development of policies to foment the adoption of sustainable practices, as well as the deployment of Extension systems to educate the general population, are likely important steps in overcoming the lack of adoption of sustainable practices. A comprehensive collaborative public-private approach with the aid of better shaped policy has the potential to help farms and their connected businesses make decisions that will collectively benefit all entities across the value chains regarding the different sustainability domains.

Table 1.1. Summary table of common economic sustainability indicators and their potential metrics with examples of utilization in studies or assessment methods.

Indicator	Metrics	Citations of Examples
Profitability	Net Income	Berg et al., 2017
	Gross Margin	Fabiani, Vanino, Napoli, & Nino, 2020; Lairez et al., 2023
Variability of Profit	Vulnerability	Konefal et al., 2023
	Variation in net income	Musumba et al., 2017
	Probability of low profitability	Musumba et al., 2017
Financial Capital	Income	Rao and Rogers, 2006
	Assets	Rao and Rogers, 2006; Hani et al., 2003
	Investments	Hani et al., 2003
Resilience	Income and crop diversity	Rao and Rogers, 2006

Table 1.2. Summary table of common environmental sustainability indicators and their potential metrics with examples of utilization in studies or assessment methods.

Indicator	Metrics	Citations of Examples
Global Warming	GHG emissions	
	Carbon dioxide emissions	Lee and Inaba, 2004
	Methane emissions	Linguist et al., 2012
	Nitrous oxide emissions	Linguist et al., 2012
Eutrophication	Nitrogen runoff	Young et al., 2021
	Phosphorus runoff	Young et al., 2021
Water Quality	Nitrogen leaching	Fabiani, Vanino, Napoli, & Nino, 2020
Water use	Use of irrigation	Gómez-Limón & Sanchez-Fernandez, 2010
Fertility	Nutrient Balances	Rao and Rogers, 2006
	Nitrogen	Hani et al., 2003;
	Phosphorus	Hani et al., 2003;
	Soil buffer capacity maintenance	Lairez et al., 2023
Energy	Energy Use	Fabiani, Vanino, Napoli, & Nino, 2020; Hani et al., 2003
	Energy Balance	Gómez-Limón & Sanchez-Fernandez, 2010
Carbon Sequestration	Carbon Balance	Yousefi et al., 2014, Q. Liu et al., 2022
Soil Erosion	Erosion control	Lairez et al., 2023; Rao and Rogers, 2006
Biodiversity	Crop diversity	Pacini et al., 2003
	Insect diversity	Pacini et al., 2003
Acidification	Acidification	Lee and Inaba, 2004
Ecotoxicity	Chemical emissions to environment	Lee and Inaba, 2004
	Herbicide leaching control	Lairez et al., 2023

Table 1.3. Summary table of common social sustainability indicators and their potential metrics with examples of utilization in studies or assessment methods.

Indicator	Metrics	Citations of Examples
Equity	Access to knowledge	Rodriguez et al., 2021; FAO, 2014
	Access to resources	Rodriguez et al., 2021; FAO, 2014
	Access to markets	Rodriguez et al., 2021; FAO, 2014
	Gender equality	Hutchins & Sutherland, 2008
Agricultural employment	Hours of work required	Gómez-Limón & Sanchez-Fernandez, 2010
Stability of the workforce	Population stability	Gómez-Limón & Sanchez-Fernandez, 2010

Table 1.4. Summary table of common production sustainability indicators and their potential metrics with examples of utilization in studies or assessment methods.

Indicator	Metrics	Citations of Examples
Land Productivity	Yield, biomass production	Lairez et al., 2023; Young et al., 2021
	Variation in productivity	Musumba et al., 2017
Yield-Gap	Difference between actual and potential or water-limited yield	Mueller et al., 2012
Input use efficiency	Yield per unit input	Musumba et al., 2017; Rao and Rogers, 2006
Cropping intensity	Number of crops harvested per year	Musumba et al., 2017; Rao and Rogers, 2006

Table 1.5. Summary table of common human condition sustainability indicators and their potential metrics with examples of utilization in studies or assessment methods.

Indicator	Metrics	Citations of Examples
Food Safety	Disease risk	Gustafson et al., 2016
	Pesticide residue	Carvalho et al., 2006
	Mycotoxin content	Wagacha & Muthomi, 2008
Food Quality	Quality Standards	Konefal et al., 2023
	Nutrient Density	Gustafson et al., 2016
	Protein production	Musumba et al., 2017
Food security	Caloric production	Musumba et al., 2017

Table 1.6. Summary table of studies evaluating the sustainability of wheat production systems, including category evaluated, location of the study, study method, and major findings.

Category	Reference	Location	Study Type	Summary
Sustainability Assessment	Goucher et al., 2017	United Kingdom	LCA	The use of nitrogen fertilizer in wheat production accounted for the largest portion of environmental impact that results from bread loaf production.
	Keikha et al., 2023	Iran	LCA	The arid climate had higher environmental impacts than the humid climate. Both climates saw increased income and water productivity at higher nitrogen rates, despite adverse ecological effects.
	Masuda, 2016	Japan	LCA	Wheat grown in both paddy and upland fields can be eco-efficient when adequate nitrogen rates are used, as opposed to excess applications which result in increased eutrophication.
	L. Zhang et al., 2021	China	LCA	Optimal nitrogen rates based on in-season measurements compared to conventional rates greatly reduced ecological impacts per unit of grain by reducing total emissions.
	Shrestha et al., 2020	United States	LCA	Wheat in rotation between oilseeds and legumes recorded the lowest environmental harm; however, midpoint impact results did not reflect other benefits of low-yielding crops to the cropping system.
	Xu et al., 2022	China	LCA	Wheat had lower environmental effects in a majority of impact categories over grain and forage maize, but alfalfa and forage maize had lower effects on air quality due to the common practice of burning wheat residues.

Category	Reference	Location	Study Type	Summary
	Ingrao et al., 2021	Global	Review	Wheat residue used for biofuels was ecologically beneficial, but less so than other residues with higher ethanol potential and biomass yields such as maize.
	Taki et al., 2018	Iran	LCA	Irrigation reduced pollution per unit of wheat produced due to higher yields, with diesel fuel and chemical fertilizers being hotspots in both irrigated and rainfed systems.
	Verdi et al., 2022	Italy	LCA	Increases in wheat yield in organic farming and reduced nutrient losses in conventional farming can decrease environmental impacts. Organic farming had lower ecological impacts than conventional in all categories except land use.
	Deng et al., 2021	China	LCA	Wheat cultivation was the main driver of sustainability in wheat supply chain, while the highest reduction in environmental effects occurred under optimal crop management and integration of supply chain steps.
	Ghasemi-Mobtaker at al., 2019	Iran	LCA	In Iranian wheat production, electricity for irrigation and fertilizer represented the highest energy consumptions.
	Fabiani, Vanino, Napoli, & Nino, 2020	Italy	WEF	Mineral fertilizers contributed to higher economic gains while organic fertilizers better preserved water quality and reduced emissions, so adoption of organic fertilizers can be driven by policy.
	Chatelin et al., 2007	France	Case Study	The study simulated crop management strategies that limited the risk of nitrogen pollution while maintaining yields and quality.

Category	Reference	Location	Study Type	Summary
	Fischer et al., 2022	Mexico	Case Study	Environmental sustainability was considered good in the Yaqui Valley and further increases in worldwide production will depend on closing yield gaps in developing countries.
	Zhao et al., 2019	China	Case Study	Using energy analysis, the most efficient region of China for wheat production was identified as the subhumid monsoon climate zone, indicating where wheat production should be focused.
	Mayer et al., 2015	Switzerland	Field Study	Organic fertilizer management resulted in lower yields due to low mineral nitrogen availability, although conventional management benefited from organic additions to the soil.
	Mustafa et al., 2021	Pakistan	Farmer Survey	Soil conservation and tree plantation increased wheat yield more efficiently as compared to changing crop varieties and planting dates, but all four environmentally friendly farming strategies were beneficial.
	Zingale et al., 2022	Global	Review	Major issues to address in durum wheat production involve productivity, environmental quality, biodiversity, intensity optimization, and fossil fuel reliance.
GHG Emissions	Monteleone et al., 2015	Italy	LCA	The best environmental performance for GHG emissions balance was achieved when using wheat residue for energy production in a rotation with an herbage crop preserve soil quality.
	Biswas et al., 2010	Australia	LCA	Emissions on the farm were higher than those associated with the production and transport of inputs, with nitrous oxide being the largest GHG emission source in wheat production.

Category	Reference	Location	Study Type	Summary
	Riedesel et al., 2022	Germany	LCA	Improved genetics for yield compensated for increased GHG emission per unit land, while low carbon footprints were associated with large farms, hybrid breeding, and fungicide use.
	Shi et al., 2021	Canada	Modelling	Most GHG emissions were connected to nitrogen through its manufacture, storage, transportation or application, and were affected by environmental impacts on nitrous oxide emissions.
	C. Wang et al., 2022	China	Field Study	Delayed planting, delayed spring irrigation, and no-tillage resulted in yield decreases, while delayed planting and tillage increased N ₂ O emissions. Nitrogen fertilizer rates between 120 and 150 kg N ha ⁻¹ maximized yield while reducing N ₂ O emissions.
Energy	Avlani & Chancellor, 1977	United States	Energy Balance	Although more energy is used for wheat production and use, it is much smaller than other reported values for flour and cereals and for all food, making it efficient as a food source comparatively.
	Safa & Samarasinghe, 2011	New Zealand	Modeling	Fertilizer and electricity accounted for about 69% of total wheat production energy consumption, and a model was created to predict energy use.
Soil Quality	Bakht et al., 2009	Pakistan	Field Study	Crop productivity and nitrogen uptake were increased when crop residues were retained or when a legume was incorporated into the cropping system.
	Ghimire et al., 2015	United States	Field Study	Residue retention, green manure, or animal manure applications reduced soil organic carbon and nitrogen depletion in the soil in this long-term study.
	B.-Y. Liu et al., 2022	China	Meta-analysis	Water and nitrogen can be saved with residue retention and subsoiling, practices that are recommended to increase yields,

Category	Reference	Location	Study Type	Summary
				decrease evapotranspiration and thus increasing crop water use efficiency.
	Carof et al., 2007	France	Field Study	When mixed with living mulch, wheat will not have competition for light when the mulch is controlled chemically or mechanically and is selected for lower height. Nitrogen uptake was not consistently affected by the presence of the living mulch.
	Miransari & Smith, 2019	Global	Review	Production under saline conditions can be sustainably increased using a combination of practices such as crop breeding, microbes, seed priming, and genotypes with natural tolerance to salinity.
	Imran et al., 2021	Pakistan	Field Study	The combination of both organic and inorganic fertilizers had the highest potential to achieve high yields while maintaining soil health.
Fertility	Kang et al., 2005	India	Field Study	Using a soil quality-based sustainability assessment with parameters of nutrient, microbial, and crop indices, organic inputs greatly increased sustainability while inorganic fertilizers reduced soil productivity microbial activity.
	Q. Zhang et al., 2017	China	Field Study	Additions of organic matter and maintaining soil cover on sloped farmland reduced phosphorus losses associated with water erosion.
	Salim & Raza, 2020	Pakistan	Review	Wheat cultivars selected for better nutrient use efficiencies will help optimize yield in deficiency scenarios for higher global food security.
	Panhwar et al., 2019	Global	Review	Outlines current knowledge on wheat plant nutrition, effects of mineral fertilizer, nutrient use efficiencies, and the use of

Category	Reference	Location	Study Type	Summary
				integrated plant nutrient management for sustainable wheat production.
Technology	Fabiani, Vanino, Napoli, Zajíček, et al., 2020	Greece and Czech Republic	Case Study	While variable rate technology is limited due to high investment costs, it has the potential to reduce environmental impacts of nitrogen losses.
Grain Quality	Cappelli and Cini, 2021	Global	Review	Strategies to improve sustainability of wheat products are explored, ranging from management in the field to innovations in the milling and baking processes.
	Cheli et al., 2013	Global	Review	The milling process reduces mycotoxins in the part for human consumption but concentrates it in by-products. Cleaning is an efficient way to reduce mycotoxins prior to the milling process.

Table 1.7. Summary table of studies evaluating the sustainability of maize production systems, including category evaluated, location of the study, study method, and major findings.

Category	Reference	Location	Study Type	Summary
Sustainability Assessment	Sadeghi et al., 2018	Iran	LCA	Emissions increased with increased nitrogen rates, but environmental effects were reduced when higher-yielding genotypes are selected.
	Grassini et al., 2012	United States	LCA	Producing high yielding maize with large net energy yield and low global warming potential concomitantly is possible. The authors identified management practices associated with this scenario.
	Yao et al., 2021	China	LCA	Applying a mixture of controlled-release urea and conventional urea at the optimal nitrogen rate minimized ecological impacts while maintaining yield compared to pure conventional urea.
	Kim et al., 2009	United States	LCA	Collecting maize stover in addition to grain reduces most environmental impacts but has the potential to negatively influence soil organic carbon levels.
	Król-badziak et al., 2021	Poland	LCA	Reduced and no-tillage resulted in less environmental impacts compared to conventional tillage, while conventional tillage performed best for social and economic effects.
	Boone et al., 2016	Belgium	LCA	Large differences in environmental impacts were caused by weather variation, while impacts could be reduced with future improved genetics. Large variation exists between similar datasets of different regions, highlighting the need for local data.

Category	Reference	Location	Study Type	Summary
	Giusti et al., 2022	Brazil	LCA	Global warming potential and eutrophication potential were driven by fertilization, acidification potential and abiotic depletion potential were mostly influenced by transportation, and the hotspot for freshwater aquatic ecotoxicity potential was identified as pesticide losses.
	Kim et al., 2014	United States	Review of LCAs	Despite using similar methodologies, studies differ regarding nitrous oxide emissions, soil organic carbon effects on emissions, labor, and machinery production impacts.
	Lairez et al., 2023	Laos	Case Study	Current maize-based systems with recent adoption of mechanization pose environmental risks with herbicide and soil management, while also showing poor economic performance.
Sustainability Adoption	Jones-Garcia & Krishna, 2021	Global South	Review	Technology adoption by farmers is limited by information accessibility and the large-scale focus of technologies.
GHG Emissions	Hill et al., 2019	United States	Case Study	Ammonia and GHG emissions result in reduced air quality responsible for premature deaths and contribution to climate change.
	Yousefi et al., 2014	Iran	Case Study	The reduction of GHG emissions and environmental impact are dependent on the efficient use of energy.
Residue Management	Adler et al., 2015	United States	Field Study	Partial stover removal can be sustainable when soil nutrients are monitored and replaced with the incorporation of no-tillage and cover crops.

Category	Reference	Location	Study Type	Summary
	Karlen et al., 2011	United States	Field Study	50% and 90% stover removal rates could result in a decline in total organic carbon which should be monitored and can be addressed through cover crops and high plant populations.
	Tiammee & Likasiri, 2020	Thailand	Modeling/ Case Study	Burning residue causes environmental impacts through GHG emissions which can be reduced by other removal methods that result in low reductions of total profits when considering social cost.
	Afshar & Dekamin, 2022	United States	Field Study	No-tillage system performed better than moldboard plow tillage, chisel plow tillage, and strip-tillage for environmental, energy and economic indicators using the LCA-MFCA method.
	Kong, 2014	China	Review	Residue retention paired with reduced tillage can increase soil quality and subsequent wheat yields compared to residue removal with conventional tillage.
Fertility	Kim & Dale, 2008	United States	Field Study	Increasing nitrogen application rates cause greenhouse gas emissions to decrease at low yields until a certain threshold where nitrous oxide emissions are higher than GHG reductions, showing there is an environmentally optimal nitrogen rate for GHG emissions.
	Tamagno et al., 2022	North America, Europe, China	Global Analysis of Field Studies	Nitrogen balance and nitrate losses can be reduced with increases in grain yield from increased nitrogen use efficiency.

Category	Reference	Location	Study Type	Summary
	J. Zhang et al., 2007	United States	Field Study	Nitrogen stress as indicated by chlorophyll content does not always result in potential yield reduction, showing potential for overapplication and nitrogen losses.
	S. Huang et al., 2010	China	Field Study	Long-term inorganic fertilizer application resulted in declining yield trends, while manure application resulted in increasing yield trends and soil quality.
Genetic Modification	Glaser & Matten, 2003	United States	Review	Review of practices and governmental restrictions intended to manage insect resistance to the Bt gene.
	Aerni et al., 2011	Switzerland	Field Study	When given product choices with a GM ingredient, Swiss consumers value the ability to choose and transparency.
	Brookes & Dinh, 2021	Vietnam	Farmer Survey	The use of GM maize increases yields and reduces costs of production, while also reducing the use of insecticides and herbicides.
Grain Quality	Geus et al., 2008	United States	Field Study	Seed quality was reduced when using a low input system as opposed to a conventional system.

Table 1.8. Summary table of studies evaluating the sustainability of rice production systems, including category evaluated, location of the study, study method, and major findings.

Category	Reference	Location	Study Type	Summary
Sustainability Assessment	Soam et al., 2017	India	LCA	Utilizing rice straw for energy production as an alternative to burning increased environmental performance for global warming, acidification, and photochemical oxidant creation potentials.
	Giuliana et al., 2022	Italy	LCA	Irrigation was identified as a major hotspot for environmental effects, indicating that changes in water management could reduce ecological impacts.
	X. Liu et al., 2020	China, India, United States	LCA	Net negative environmental impacts were documented in all three studied countries, which economically represented 2-6% of the price of rice.
	Ahmad et al., 2023	Global	Review of LCAs	Most LCA studies evaluate global warming potential and acidification potential, while few consider biodiversity, soil organic carbon, and fertility.
	Mungkung et al., 2022	Thailand	Survey	The highest Sustainable Rice Platform (SRP) scores were associated with good farm management, IPM, water use, and health and safety, showing that SRP scores can be useful to detect problem areas regarding sustainability.
	Stuart, Pame et al., 2018	Thailand	Field Study	Using best management practices, fertilizer and seeding rates can be reduced while still maintaining similar yields to the standard farmer practices, thus increasing income and reducing ecological effects.

Category	Reference	Location	Study Type	Summary
	Stuart, Devkota, et al., 2018	Vietnam	Survey and Field Study	Using the ‘One Must Do, Five Reductions’ initiative, inputs with negative ecological effects could be reduced while increasing net income.
	Devkota et al., 2020	India	Survey	Machine transplanted rice promotes higher yields and profit, while there is room for improvement in fertilizer, irrigation, pesticide, and labor use to close the yield gap and improve sustainability.
	Roy et al., 2014	Bangladesh	Survey	Increasing information availability and land productivity, developing human capital, and conserving resources were the central themes that promote rice sustainability in Bangladesh.
	Devkota et al., 2019	Asia	Survey	Optimizing fertilizer use, reducing water, pesticide, and labor use, and adopting high-yielding genotypes are the main avenue that would lead to higher sustainability in several Asian countries.
	Mishra et al., 2022	Global	Review	Rice producers were positively impacted by several technologies including improvements in genotype, management, post-harvest technology, decision tools, and training and information programs.
	Nawaz et al., 2022	Global	Review	The adoption of integrated crop management, development of genetic tolerance to stresses, and policy support for suitable machinery can increase sustainability of flooded rice systems.
	Yuan et al., 2021	Global	Yield-Gap Analysis	Focusing on those systems with large yield-gaps and low resource use efficiencies could be key to increasing global rice supply while reducing environmental impacts.

Category	Reference	Location	Study Type	Summary
Sustainable Intensification	Pittelkow et al., 2016	Uruguay	Review	Yield, net energy, and water use efficiency increased with intensification of rice production, which decreased the per unit carbon footprint but increased risks of nitrogen losses and chemical contamination.
	Tseng et al., 2020	Uruguay	Field Study	Increasing yields compared to high-yielding farmers resulted in negative environmental impacts, emphasizing the need for environmental analysis on yield-improving field research trials.
Sustainability Adoption	Conner et al., 2021	Indonesia	Survey	Farmers viewed the adoption of climate-smart agriculture as an avenue to reduce poverty, with improved varieties and alternate wetting and drying being the most adopted practices.
	Ashoori et al., 2017	Iran	Survey	The adoption of conservation practices is influenced by producer's income, age, access to supplies and main roads, and use of irrigation from canals.
	Rahman and Bulbul, 2015	Bangladesh	Survey	The adoption of alternate wetting and drying, a practice that can reduce methane emissions and water use, could be increased through contact with extension personnel.
GHG Emissions	Jirapornvaree et al., 2021	Thailand	LCA	Emissions were higher in organic rice production than conventional practices, but this was attributed to higher soil organic matter and organic soil amendments in organic production fields.
	Nunes et al., 2016	Brazil	LCA	Organic rice had higher emissions due to the practice of flooding, while cultivation and inorganic fertilizer were identified as emission hotspots.

Category	Reference	Location	Study Type	Summary
	Brodt et al., 2014	United States	LCA	High-yielding intensive production systems do not always impact the environment more than low-input systems.
	Rahman et al., 2019	Malaysia	LCA	The largest GHG source in rice production was methane emissions, which could be reduced with different straw degradation practices and the use of alternate wetting and drying.
Residue Management	A. Kumar et al., 2022	Global	Review	Effective management of rice residue or using rice residue for alternative uses as opposed to the common practice of straw burning can promote sustainability.
	R. Kumar et al., 2020	India	Field study	Using direct seeding with no-till, retaining rice residue, and intensifying with a winter crop can help improve productivity and economics, while increasing energy use efficiency and decreasing GHG emissions.
	J. Zhang et al., 2021	China	Field Study	Soil fertility and rice yield stability were increased when straw was incorporated compared to straw removal under high fertility conditions.
	T. Li et al., 2019	China	Field Study	Soil health and rice yield performance was promoted most by returning rice straw to the field following harvest both crops and by using a green-manure crop between the late-season and early-season rice crops.
	G. Zhou et al., 2020	China	Field Study	Improvements in soil quality and rice yields were observed when a legume green manure and rice residue were incorporated into the soil prior to rice planting.

Category	Reference	Location	Study Type	Summary
	Nguyen-Van-Hung et al., 2019	Philippines	Field Trial	Net energy was increased by removing residue for use in mushroom production compared to burning residue, while at least partial residue removal reduced GHG emissions compared to complete retention or incorporation.
	Sharma et al., 2020	Global	Review	Using residues for biofuels can reduce GHG emissions and produces energy compared to traditional burning of rice straw; recent literature on this subject is discussed.
	Harun et al., 2022	Global	Review	Compared to fossil fuel energy production, utilizing rice straw could result in reduced global warming potential, but more studies are needed to assess other factors in its sustainability.
	Singh et al., 2021	Global	Review	As an alternative to rice straw burning, electricity generation or incorporation with the soil are the least ecologically impactful methods of residue management.
Soil Quality	Biswas et al., 2017	India	Field Study	Key indicators of soil quality in rice production systems were identified for the three major soil orders of India including Inceptisols, Entisols, and Alfisols.
	S. Zhang et al., 2023	China	Field Study	Compared to annual rice, perennial rice improved soil quality parameters, decreased labor requirements and input costs, and produced similar yield.
Fertility	Zhuang et al., 2022	China	Collection of Field Studies	Optimizing fertilizer applications paired with straw incorporation and the use of green manures can reduce ecological effects while maintaining rice yield.
	Liang et al., 2017	China	Field Study	Using optimal nitrogen rates with alternate wetting and drying at a 15cm water depth could increase nitrogen and

Category	Reference	Location	Study Type	Summary
				water use efficiencies, also resulting in reduced nitrogen losses and GHG emissions.
	Yu et al., 2014	China	Field study	Nitrogen fertilizer applications can be reduced, nitrogen losses reduced, and grain yield maintained when incorporated a legume in the cropping system
	Fageria et al., 2003	Global	Review	Best management practices regarding the sustainability and efficiency of nutrient management in rice production are discussed.
Water Management	Miniotti et al., 2016	Italy	Field Study	Dry seeding with intermittent irrigation increased water use efficiency and decreased GHG emissions but yielded lower than wet seeding with continuous flooding and dry seeding with flooding at the tillering stage.
	Moreno-García et al., 2021	United States	Field Study	Furrow irrigation and alternate wetting and drying showed the greatest reductions in GHG emissions, although chemical applications in furrow irrigation increased energy usage.
Biodiversity	Luo et al., 2014	China	Review	Increasing biodiversity, rotations, reduced use of chemicals, and incorporation of animals and other plants are ways to increase ecological sustainability in paddy rice systems.
	Gautam et al., 2021	India	Field Study	Increases in sustainability, productivity, and profitability were observed when short-season rice varieties were utilized and followed by a legume crop.
	Berg et al., 2017	Vietnam	Field Survey	Integrated rice-fish farming does not affect rice yield or net profit but can reduce chemical and fertilizer inputs. Most

Category	Reference	Location	Study Type	Summary
				farmers were willing to reduce yields to improve environmental quality.
Pest Management	H. He et al., 2019	China	Review	The benefits of crop diversity are being emphasized in literature for their impact on pest control, with progress on these topics being made in China.
	Fahad et al., 2021	Global	Review	Biological control of pests can be beneficial economically and environmentally as opposed to chemical methods of control.
	Hong-xing et al., 2017	China	Review	Natural control methods are useful for partially replacing chemical control methods in the long run, but chemical means are a good choice for rapid pest outbreaks.
	Savary et al., 2012	Global	Review	The “Human-Pest-Environment-Crop” framework for sustainable pest management is discussed, with a few rice pests addressed using the framework.
Grain Quality	T. Zhou et al., 2022	China	Field Study	Organic fertilizers can improve several rice quality factors involving starch structure, protein content, microelement levels, and cooking qualities.
	Ishfaq et al., 2021	Pakistan	Field Study	Alternate wetting and drying can improve milling and grain quality as well as kernel characteristics, while reducing mercury accumulation and water inputs.
	Upadhyay et al., 2020	Global	Review	Grain contamination with arsenic coming from groundwater irrigation applications can be managed with effective watering strategies.

Category	Reference	Location	Study Type	Summary
Biofortification	Sheoran et al., 2022	Global	Review	Plant breeding, genetic modification, and fertility management have the greatest potential in the biofortification of rice to combat human malnutrition.
	Bana et al., 2022	India	Field Study	Zinc-coated urea can increase yields, nitrogen use efficiency, zinc content, and grain quality in basmati rice production.
	Peramaiyan et al., 2022	South Asia	Review	Zinc fertilizer applications along with genetics promoting zinc-enrichment can help increase its content in rice to help reduce human zinc deficiency.
	Majumder et al., 2019	Global	Review	Genetic engineering in rice has produced increases in iron, zinc, β -carotene, and other essential nutrients within the grain.
	Dubock, 2017	Global	Review	Golden Rice, a genetically modified rice genotype that produces β -carotene, could be one solution to reduce vitamin A deficiency in humans.
Consumer Preference	Connor et al., 2022	Vietnam	Survey	Consumers in Vietnam are willing to pay a premium for rice labeled as SRP-certified, while higher-income consumers with knowledge of climate change willing to pay more.
	My et al., 2018	Vietnam	Survey	Consumers are willing to pay more for sustainable rice and are willing to pay increasing amounts with addition information and traceability included on the label.
	Okpiaifo et al., 2020	Nigeria	Survey	Nigerian rice consumers value food safety more than other sustainability attributes, with environmental indicators are valued very low.

Category	Reference	Location	Study Type	Summary
	Aoki et al., 2017	Thailand and Japan	Choice experiment	Rice produced in the United States is acceptable in Thailand at a low price due to their willingness for fair trade, while Japanese people value organic rice and dislike US rice.

Table 1.9. Summary table of studies evaluating the sustainability of soybean production systems, including category evaluated, location of the study, study method, and major findings.

Category	Reference	Location	Study Type	Summary
Sustainability Assessment	Zortea et al., 2018	Brazil	LCA	Sustainability dimensions were impacted most by supply costs, eutrophication, and the local community, with the social aspect having the most room for improvement.
	Andrade et al., 2022	United States	Field studies	Production, economic, and quality aspects of soybean management intensification were assessed as compared to the typical grower management.
	Phélinas and Choumert, 2017	Argentina	Review and Field Survey	The production of genetically modified soybeans has varying impacts on the economic, environmental, and social aspects of sustainability.
	de Silva et al., 2010	Brazil	LCA	Regional differences exist in the environmental effects of soybean production in part due to transportation and deforestation, with transportation being a point of emphasis for improvements to reduce impacts.
	Dalgaard et al., 2008	Argentina	LCA	Regarding the most impactful categories, global warming potential was driven by crop residue and biological nitrogen fixation emissions, while eutrophication and acidification were greatest affected by transportation.
	Knudsen et al., 2010	China and Denmark	LCA	Organic soybean production had lower impacts than conventional. Transport by ship played a large role in emissions, while the results were sensitive to nitrous oxide emission estimations.
	Greer et al., 2020	United States	Field Study	Negative environmental impacts are not compensated by increases in potential yield under high-input management.

Category	Reference	Location	Study Type	Summary
GHG Emissions	Mohammadi et al., 2013	Iran	LCA	Increasing input efficiencies and using residue management alternatives to burning can assist in decreasing global warming potential.
	Raucci et al., 2015	Brazil	LCA	Residue decomposition, fuel, and fertilizers were the largest sources of emissions; meanwhile, no differences were observed when farm size and production intensity were considered.
	Langeroodi et al., 2019	Iran	Field Study	GHG emissions were reduced, and grain yield was maintained when using no-tillage into wheat residue with 80 kg N ha ⁻¹ .
Soil Management	Thapa et al., 2021	United States	Review	Soil factors play a role in plant response to micronutrient application; therefore, soil tests are a useful tool for determining micronutrient application rates.
	Giacomeli et al., 2021	Brazil	Field Study	No-tillage and sprinkler irrigation sustainably increase soybean yield in lowland irrigated rice systems.
Pest Management	Ragsdale et al., 2011	North America	Review	Resistant varieties and understanding relationships with other species are the keys to the sustainable management of the soybean aphid.
	Hodgson et al., 2012	United States	Review	Environmental effects and production costs can be reduced using a combination of cultural practices, genetic resistance, and chemicals when managing soybean aphids.
	Rodriguez et al., 2021	Americas	Review	Cultural control methods should be considered to minimize environmental impact when managing sudden death syndrome sustainably.
	Bueno et al., 2021	United States & Brazil	Review	Although facing challenges with adoption, integrated pest management recommendations should be farmer specific while being sustainable environmentally and economically.

Category	Reference	Location	Study Type	Summary
Yield-Gap	Sentelhas et al., 2015	Brazil	Modeling/Case Study	Yield gaps of ~42% resulting from water deficit and management were observed, indicated potential production increases without land expansion.
Storage	Coradi et al., 2020	Brazil	Field Study	Harvesting at a high moisture content and drying continuously in storage to 11-12% moisture provided the best combination of grain quality and performance.
Supply Chain	Jia et al., 2020	Global	Review	Barriers, consequences, mechanisms of governance, and drivers of sustainable supply chain management are discussed.
	Teuscher et al., 2006	Global	Case Study	Sustainable supply chain management is discussed with the example of non-GMO soybeans.

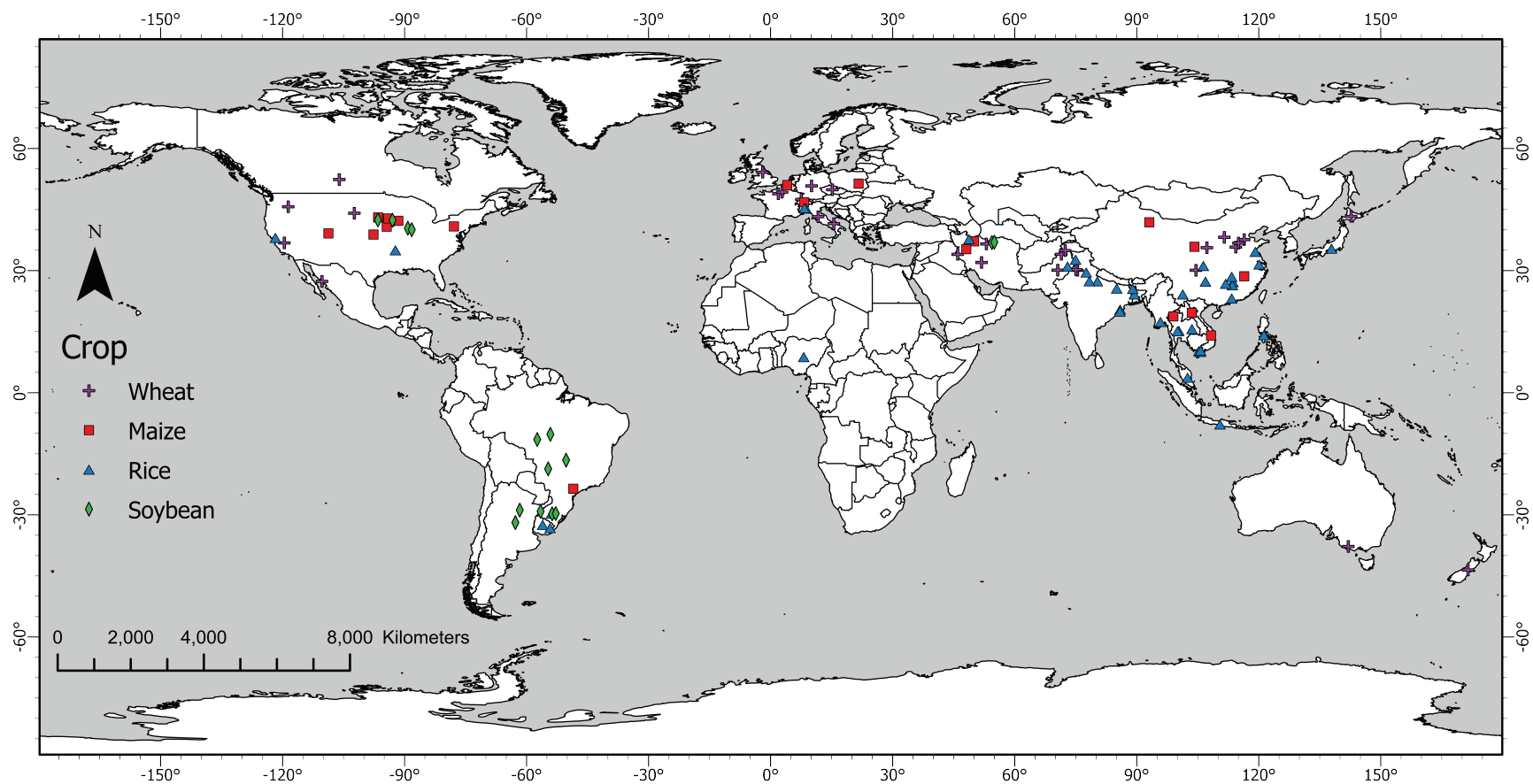


Figure 1.1. Global distribution of sustainability studies regarding the four major agricultural crops included in this review, excluding 24 studies that were conducted in multiple countries or globally.

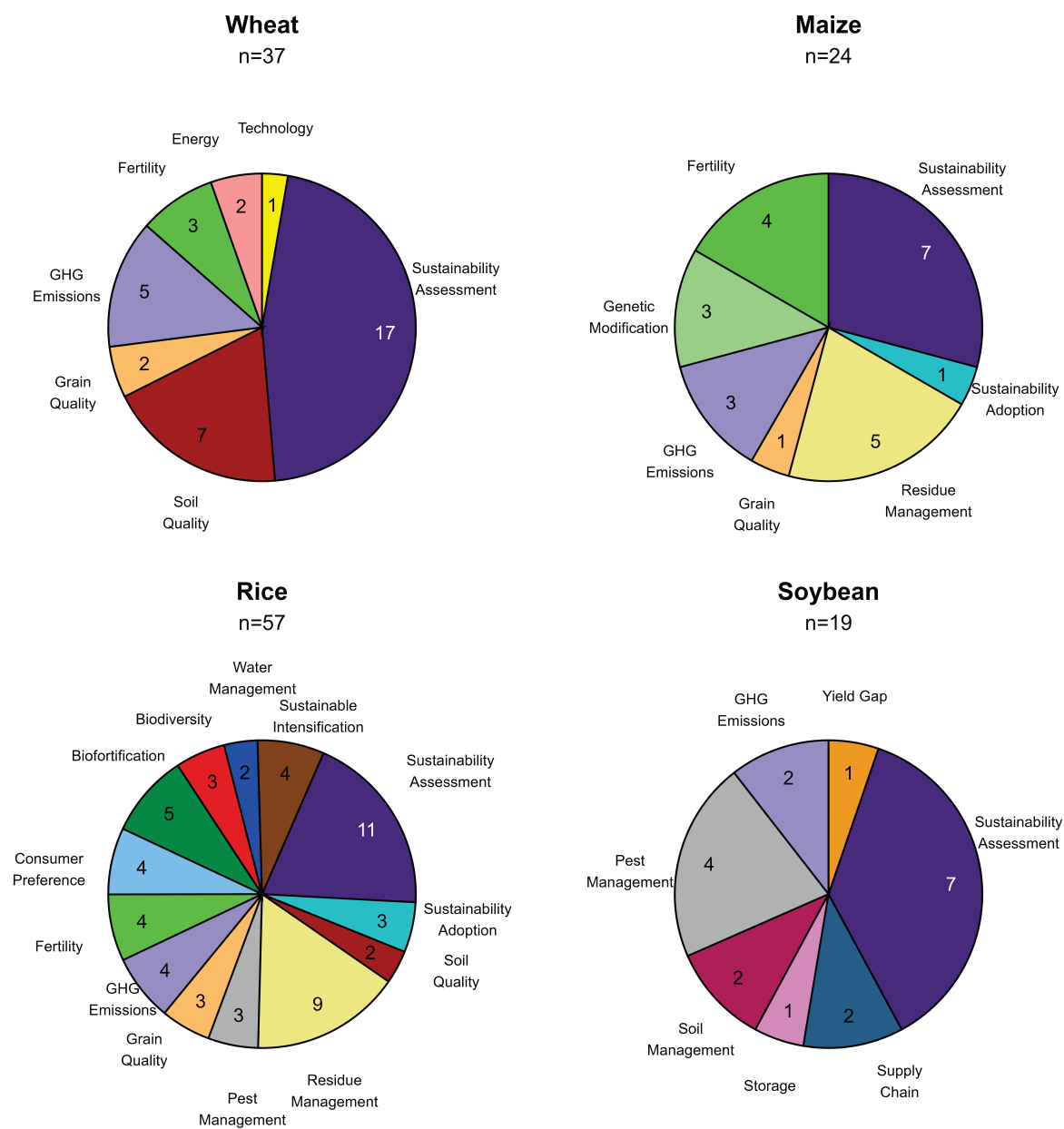


Figure 1.2. Distribution of sustainability literature by study subject for the four major agricultural crops included in this review.

Chapter 2 - Can sustainable intensification of wheat production increase bread yield while maintaining global warming potential?

Abstract

The need for increased food production to supply the growing population coupled with environmental concerns surrounding global warming potential calls for the sustainable intensification of crop production. Life cycle assessment (LCA) provides a means for quantifying the environmental impacts of intensifying wheat production management relative to the quantity produced. We established field experiments where we replicated the management intensities currently adopted in commercial wheat (*Triticum aestivum* L.) fields to identify avenues to increase bread production while improving or maintaining environmental footprints. Four management intensities (i.e., low, average, high, and top) were derived from a survey of 656 commercial winter wheat fields and replicated in trials conducted in 23 site-year combinations in the sub-humid and semi-arid regions of Kansas to quantify yield and carbon residue return to the soil. Milling and baking analysis characterized the loaf of bread. Cradle-to-grave LCA quantified global warming potential (GWP) and energy inputs relative to a functional unit of 1 kg of bread, while estimates of carbon sequestration and bread energy output allowed the calculation of net GWP and net energy yield (NEY). As management intensified, both grain yield and protein increased (+ 0.5 Mg ha⁻¹ and + 0.4% from average to high managements) despite a negative relationship between the two within management intensity. The combination of higher yield and protein increased bread yields ($R^2 = 0.86\%$). GWP and energy inputs for both the wheat production phase and the entire bread production system increased as a result of added

inputs with each step of intensity (+ 0.08 kg-CO₂e and + 0.49 MJ per kg-bread⁻¹), but the magnitude of increase was alleviated by increases in bread yield in more intensive managements when variables were yield-scaled. Estimates of carbon sequestration (range: 0.25 to 1.25 Mg ha⁻¹) helped to offset the environmental footprint of bread production, especially in higher yielding conditions that also returned more residue to the soil ($R^2 = 0.54$). Thus, although mean GWP and energy input increased with more intensive management (1.22-1.46 kg-CO₂e and 15.02-16.34 MJ per kg-bread⁻¹), differences among treatments decreased as bread yield increased. These results suggest an opportunity to substantially increase bread yields with minor increases in environmental impact per unit bread.

2.1 Introduction

There is a pressing need to increase food production and nutrition while minimizing the potential impacts of climate change (Parry et al., 2010). This need is aggravated by geopolitical conflicts which are especially relevant in the case of wheat (*Triticum aestivum* L.), a commodity that supplies ~20% of human-consumed calories and protein globally (Shewry and Hey, 2015) and whose international supply may suffer shortages due to the recent Russia-Ukraine conflict (Júnior et al., 2022; Al-Saidi, 2023).

Feeding the world without massive cropland expansion requires increases in grain yield, which can be attained through management intensification (Foley et al., 2005; van Ittersum et al., 2013). Many studies have recently evaluated the potential of management intensification to increase wheat grain yield (Jaenisch et al., 2019, 2022; Quinn et al., 2019; Peterson et al., 2023; Roth et al., 2021). The majority of these studies used replicated field experiments where treatments (i.e., combinations of management practices) were determined by the leading researchers, which may not reflect the level of technology adoption in real world scenarios

(Andrade et al., 2022). An alternative is to perform on-farm surveys of management adoption and associated grain yield that allow for exploration of larger number of variables (e.g., Grassini et al., 2015; Jaenisch et al., 2021; Lawes et al., 2021). These, however, are not structured or replicated and only allow researchers to derive correlations and not causations. A compromise between both approaches is to evaluate, in replicated trials, combinations of management practices that reflect those adopted by different cohorts of producers with contrasting yield levels based on data collected via on-farm surveys of commercial fields (e.g., Andrade et al., 2022). We are not aware of studies focused on wheat using this approach.

Management intensification may result in increased environmental impacts (e.g., greenhouse gas [GHG] emissions), especially in a context where the agriculture sector already accounts for about 22% of GHG emissions globally (Shukla et al., 2022). The environmental impacts of production agriculture are well documented, including nitrous oxide emissions from nitrogen fertilizer (Eichner, 1990; Freney, 1997; Reay et al., 2012), eutrophication from nitrogen and phosphorus fertilizer (Bennett et al., 2001; Daniel et al., 1998; L. Liu et al., 2021), diesel combustion emissions from machinery usage (Dyer & Desjardins, 2003; Guo et al., 2020), toxicity of chemicals (Berthoud et al., 2011; Lundie et al., 2007; Peña et al., 2019), among many others. Equally as important are upstream environmental impacts associated with the manufacture of agricultural inputs (Basosi et al., 2014), which in total would increase with higher input rates adopted in intensive management. Still, there is evidence for the potential of agricultural practices to reduce the environmental impacts of the sector (Johnson et al., 2007). Therefore, it is important to assess both the potential gains in production concomitant with environmental indicators when assessing management intensification (Greer et al., 2020). Meanwhile, to our knowledge, the recent efforts evaluating management intensification of wheat

production (e.g., Jaenisch et al., 2019, 2022; Quinn et al., 2019; Peterson et al., 2023; Roth et al., 2021) have focused mostly on yield and other production variables, largely overlooking environmental factors.

In addition to upstream environmental impacts, management decisions at the production level can affect factors ultimately impacting the efficiency of downstream processes (Liska et al., 2009). In wheat, field management can modulate kernel characteristics that impact attributes related to end-use quality, such as milling and dough rheological properties, consequently impacting bread quality (Raj et al., 2023). For example, application of foliar fungicides in the field can impact grain characteristics such as kernel weight and density (Cruppe et al., 2017, 2021; Jaenisch et al., 2019) that can impact flour yield (Raj et al., 2023), which in turn would have a direct impact on the efficiency of the milling process (Bojanić et al., 2021). Increasing this efficiency would potentially produce more product per unit of wheat grain and per unit land. Likewise, nitrogen fertilizer management can impact grain protein concentration (Lollato et al., 2019, 2021) which impacts dough rheology and bread volume (Corassa et al., 2018; Raj et al., 2023). Therefore, grain quality aspects can have a direct impact on different indicators of sustainable intensification. In this way, management decisions are directly linked to environmental impacts both upstream and downstream from the production phase.

Intensification of management with higher input rates will inevitably increase environmental impacts on an area basis, which can lead to underestimations of the impacts of low-input systems (Balmford et al., 2018). Due to the pressing need to feed a growing global population, impact assessments must also be performed production-scaled to determine environmental effects relative to the positive effects of management intensification (e.g., Grassini and Cassman, 2012). Thus, methods that account for upstream and downstream

environmental impacts scaled to production have the potential to accurately determine the effects of agricultural management decisions across the value chain. Life cycle assessment (LCA) is one of several tools that can be used to assess the environmental outcomes of a given system and is especially useful when making direct comparisons among systems of interest (Clark & Tilman, 2017; Meier et al., 2015; Schmidt, 2010). LCA provides a structured method for quantifying environmental impacts throughout a product's entire life cycle as a function of a specified unit of production. This is useful to determine overall ecological effects, as well as to identify hotspots within different parts of the product system. Implementation of LCA in agriculture is common for the major food crops including maize (*Zea mays* L.) (Kim et al., 2009; Li et al., 2021), soybean (*Glycine max* (L.) Merrill) (Brito et al., 2021; da Silva et al., 2010; Mohammadi et al., 2013), and rice (*Oryza sativa* L.) (Gathorne-Hardy, 2013; Habibi et al., 2019; He et al., 2018; Jimmy et al., 2017; Jirapornvaree et al., 2021; X. Liu et al., 2020; Rahman et al., 2019; Soam et al., 2017; Van Hung et al., 2020; Wang et al., 2010). In addition, wheat production has been widely explored using LCA, including studies investigating specific inputs such as fertilizers (Charles et al., 2006; Fallahpour et al., 2012; Keikha et al., 2023), tillage methods (Houshyar & Grundmann, 2017), and organic production (Meisterling et al., 2009). General LCA studies on wheat production have investigated global warming potential (GWP) (Biswas et al., 2010; Riedesel et al., 2022), energy use (Taghavifar & Mardani, 2015), ecotoxicity (Berthoud et al., 2011), and more comprehensive environmental impacts (Holka, 2016; Shrestha et al., 2020). However, we note that most LCA studies on wheat or bread either (i) did not evaluate combinations of management practices for sustainable intensification, (ii) concluded at the farm-gate (i.e., grain rather than bread), or (iii) were not based on replicated plot data and simply on aggregated data.

The central hypothesis of this work is that certain combinations of practices currently adopted in commercial wheat fields have the potential to increase bread yield per unit area with relatively low global warming potential and energy input per unit of bread. To test this hypothesis, we used a comprehensive approach including the replication of different management intensities of wheat production as currently used by producers in commercial fields as identified via an on-farm survey, coupled with the LCA framework from cradle (i.e., manufacturing, packaging and transportation of inputs used for field production) to grave (i.e., to the production of bread) to identify avenues to increase bread production and improve or maintain environmental footprints simultaneously.

2.2 Methods

2.2.1 Theoretical framework

Yield potential is the yield attained by an adapted cultivar when grown without biotic or abiotic limitations (Evans & Fischer, 1999). In rainfed environments, water-limiting potential yield is a more useful benchmark since it accounts for limitations caused by water supply and distribution while avoiding manageable stresses (Fischer, 2015). Yield gaps are then defined as the difference between current yields and the water-limited yield (i.e., what is the additional yield that could be achieved with optimal management at given weather conditions; Fischer, 2015; Lobell et al., 2009). Narrowing yield gaps to values closer to the attainable yields have the potential to increase wheat production sustainably (Mueller et al., 2012), especially in regions of the world characterized by stagnant that are well-below their potential (Grassini et al., 2013). Winter wheat cultivated in the Great Plains region of the United States offers a unique case-study for the potential of management intensification since there is evidence for recent yield plateaus

and large yield gaps (Li et al., 2014; Patrignani et al., 2014; Schauburger et al., 2018; Lollato et al., 2017, 2019a).

2.2.2 Study region

We used the state of Kansas, US, as a case-study. With an annual area of 3.1 million hectares and an annual production of 8.8 million metric tons (USDA-NASS, 2023), Kansas ranks first in both area and production of winter wheat in the US, corresponding to about 27% and 23% of total national numbers, respectively. As highlighted above, this region offers a unique opportunity to evaluate sustainable intensification of crop production since wheat grain yield has averaged 2.8 Mg ha⁻¹ in the last 15-yr, and has rarely surpassed 3.5 Mg ha⁻¹. Still, previous evidence suggest that this grain yield is well below its water-limited yield potential (Y_w) of c.a. 5.2 Mg ha⁻¹ (Lollato et al., 2017). Therefore, this large yield gap can be potentially filled through improved management, which is what we test in the current work. The state is subject to a gradient of annual rainfall, ranging from 390-1190 mm from the west to the east (Lollato et al., 2020); consequently, the climate is considered sub-humid in central and eastern Kansas and semi-arid in the west (Sciarresi et al., 2019). Most of the wheat area is located in the central and western regions of the state and cultivated under non-irrigated conditions (Figure 2.1).

2.2.3 Field experiments

Rainfed experiments were conducted in 23 site-years resulting from the combination of growing seasons (2020-21 and 2021-22) and locations (10 and 13 per year). The experimental sites were distributed across the wheat growing areas of Kansas (Figure 2.1), covering the variation of soil and climate conditions across the state (Table 2.1). Across years, 13 experiments were conducted in the sub-humid and 10 experiments in the semi-arid portion of the state.

Environmental and management information for the experiments is shown in Table 2.1, with additional soil test and environment information shown in Table B.1 and Table B.2.

Experiments were conducted as complete factorial combinations of management intensities and winter wheat varieties arranged as split-plot design, where management constituted the whole plot and variety the sub-plot. Input levels applied in each management intensity was derived from a survey of management practices adopted in 656 commercial winter wheat fields in Kansas (Jaenisch et al., 2021). We classified fields based on grain yield into categories of “Low” (bottom 30% yielding fields), “Average” (all fields), “High” (top 30% yielding fields), and “Top” (top 5% yielding fields) yielding fields. Subsequently, we quantified the frequency of adoption and the input rate of different management practices for each group and established these combinations as replicated as treatments. Management practices that were allowed to vary included those easily modified in season (i.e., seeding rate, starter fertilizer, fertilizer rate, and pesticide management) and not those that are fixed based on cropping system (e.g., previous crop, tillage practice, sowing dates, etc.) (Table 2.2). For these fixed practices, the entire experiment adopted those that were predominant in the survey. Here, wheat was sown under no-tillage practices after a preceding soybean crop and towards mid- to late-sowing dates in the sub-humid climate, and under no-till, following a preceding 14-month fallow period after a previous sorghum crop, and sown around the optimum time in the region in the semi-arid west. The factorial combination with winter wheat varieties was established to attempt to account for the typical variety by management interaction observed in agronomic trials (Cooper et al., 2001; Hunt et al., 2021; Munaro et al., 2020; Rotili et al., 2020). In each environment, varieties adapted to each region were selected, including Zenda and WestBred (WB)-4269 in the sub-humid region, and KS Dallas and WB-Grainfield in the semi-arid region.

Treatments were established according to Table 2.2 based on their location within Kansas. Plots (12.2 m²) were sown using a Great Plains 606 no-till drill (7 rows at 19 cm spacing). Management intensities adopting seed treatment received 19.5 mg a.i. kg-seed⁻¹ mefenoxam, 121.1 mg a.i. kg-seed⁻¹ difenoconazole, and 394.5 mg a.i. kg-seed⁻¹ thiamethoxam. Phosphorus requirements and partial nitrogen requirements were fulfilled using diammonium phosphate (18-46-00) fertilizer placed in-furrow with the seed at planting. The remaining required nitrogen was applied as urea by hand at Zadoks GS 26 or, for selected treatments, split applied at Zadoks GS 26 and Zadoks GS 31 (Zadoks et al., 1974). Sulfur (ammonium sulfate) and chloride (potassium chloride) were applied by hand in selected treatments together with the Zadoks GS 26 nitrogen application. Foliar fungicide applications (i.e., 25.5-g a.i. ha⁻¹ fluxapyroxad, 190.3-g a.i. ha⁻¹ pyraclostrobin, and 118.5-g a.i. ha⁻¹ propiconazole) occurred using a CO₂-pressurized backpack sprayer at Zadoks GS 31 and Zadoks GS 60 for the jointing and flag-leaf applications, respectively. Micronutrients (i.e., 217 g ha⁻¹ sulfur, 6 g ha⁻¹ boron, 181 g ha⁻¹ manganese, and 241 g ha⁻¹ zinc) were applied in conjunction with the jointing fungicide. Entire plots were harvested with a Massey Ferguson 8XP small plot, self-propelled combine. Timings of applications and operations are summarized in Table 2.1.

2.2.4 Measurements

Biomass samples were collected from a 0.19 m² area just prior to harvest. Samples were dried at 65°C for dry mass determination, before being partitioned into stover, chaff, and grain. Grain protein content was then determined using near-infrared reflectance spectroscopy and also adjusted to 13% moisture basis. Stover and chaff were combined and ground to pass a 2-mm mesh and the grain was ground separately, before being tested for total carbon content. Carbon content was measured using a LECO TruSpec CN combustion analyzer and reported on a weight

percent basis. Carbon content of stover and chaff was multiplied by stover and chaff mass to estimate carbon return to the soil. Grain weight, test weight, and moisture content were measured at harvest with a HarvestMaster GrainGage system mounted on the combine. Grain yield was calculated with an adjustment to 13% moisture content.

Whole-plot grain samples were collected from the combine for milling, dough, and baking quality assessments. Wheat milling was conducted according to AACC International Method 26-21.02 for Experimental Milling. First, samples from a treatment-variety-location combination were mixed and subsampled three times into 1500g samples for remaining analyses. The samples were tempered to 16% moisture content, and milling yield was calculated as the percentage of flour produced from the weight of tempered wheat. Dough characteristics, including water absorption, were determined with a farinograph using AACC International Method 54-21.01 for Physical Dough Tests. Baking quality was determined according to AACC International Method 10-10.03 using ingredient ratios for 500 grams of flour. The resulting dough was split by weight into three loafs that each contained 100 grams of flour. Each loaf contained 5.3 grams of yeast, 6.0 grams of sucrose, 1.5 grams of salt, 3.0 grams of shortening, and water based on the farinograph value for water absorption. The end weight of bread was assumed to be 16% of the starting weight of dough, which was the average of varieties at a constant protein level according to literature (Puhr & D'Appolonia, 1992).

2.2.5 Life cycle assessment goal and scope

2.2.5.1 System boundaries

LCA (ISO, 2006) compared the greenhouse gas emissions and energy use of producing white bread at different intensities of wheat production management. These were converted to a functional unit of one kilogram of bread at the consumer's home ready for use. The system

boundary includes processes in wheat production and processing from cradle to grave (Figure 2.2). The functional unit and system boundaries are similar to other recent bread LCAs (Andersson & Ohlsson, 1999; Deng et al., 2021; Kulak et al., 2015).

Wheat production processes included manufacturing, packaging, and transportation of all inputs used in the field (e.g., seed, fertilizer, pesticides) and the energy associated with sowing, applications, and harvest of the wheat crop. The processing of wheat grain after harvesting accounted for storage, transportation, milling, and baking processes. Here, we accounted for transportation of grain from farm to the elevator, from the elevator to the mill, from the mill to the baking, and transportation associated with bread distribution, retailing, and home for use. Output flows included losses through emissions including nitrous oxide, carbon dioxide, and methane emissions.

While there are 18 environmental mid-point categories that can be explored through LCA (Feng et al., 2023), here we focused only on global warming potential (GWP) and energy use to avoid potential redundancies. The GWP impact category quantifies the effects that direct and indirect greenhouse gas emissions have in relation to climate change (Dincer & Bicer, 2018; Finnveden et al., 2009). To adjust emissions to similar units for comparison, the Tool for Reduction and Assessment Chemicals and Other Environmental Impacts (TRACI) was utilized to provide impact factors for methane and nitrous oxide emissions (Bare, 2011). The energy use impact category characterizes the potential environmental impacts associated with energy use and generation (Chau et al., 2015; Taghavifar & Mardani, 2015). In addition to energy use, net energy yield was calculated by subtracting energy inputs from the energy output of bread. Net GWP was also calculated as total GWP minus carbon sequestration (resulting from stover return

to the soil). All environmental impact assessment calculations were conducted using RStudio 2023.06.1 (RStudio Team, 2020) following ISO 14040 guidelines (ISO, 2006).

2.2.6 Life Cycle Inventory

Life cycle inventory data was collated from recent academic literature, through international organizational standards for estimation, and using the Ecoinvent 3.0 database (Wernet et al., 2016) (Tables B.3, B.4, B.5). In the wheat cultivation phase, embodied emission and factors were collected for fertilizer production for nitrogen, phosphorus, potassium, and sulfur using values from the Ecoinvent 3.0 database. Since micronutrient fertilizer applications have no negative effects on LCA environmental damage categories (Hatim et al., 2023), and due to its very low application rates, it was excluded from this study. However, fuel usage associated with micronutrient applications are included since they were applied together with a fungicide application. Ecoinvent 3.0 was also used for all pesticide emissions, specific to each herbicide, fungicide, and insecticide active ingredient used. Wheat seed used at sowing was estimated using literature-reported values (West & Marland, 2002). Field emissions of nitrous oxide were also included for the nitrogen fertilizer according to the International Panel on Climate Change (IPCC) guidelines, which can be a major emission source in agricultural systems through denitrification processes (IPCC, 2006). Farm equipment fuel usage was quantified based on crop budgets developed by Agricultural Economics department and Kansas State University (Table B.6), which are specific to subregions of Kansas (Ibendahl et al., 2021, 2022). Diesel energy and emissions considered both manufacturing (Wernet et al., 2016) and combustion (EPA, 2023).

In the wheat processing phase (i.e., milling and baking), we used literature-reported energy use factors to quantify energy use and emissions associated with storage and milling of wheat, and baking and distribution of bread (Avlani & Chancellor, 1977; Table B.7). The main

technologies for these processes have been consistent over time and therefore are still representative of present practices in this comparative study (Campbell, 2007; Cappelli et al., 2020). In addition, the coefficients used for baking are similar to other literature when adjusted for similar units (Le-bail et al., 2010). These factors were adjusted based on current greenhouse gas emission use factors for natural gas, refined petroleum, and electricity from the United States Environmental Protection Agency (EPA, 2023) and manufacture of these inputs (Wernet et al., 2016). Transportation between processes used coefficients based on distance and weight (EPA, 2023) and adjusted for the manufacture of the fuel used (Wernet et al., 2016).

2.2.6.1 Transportation Assumptions

Field-to-elevator distance was assumed to be 32.2 km, which is reported by the Kansas Department of Revenue (2022) and consistent with the highest mile limits in the wheat growing areas of Kansas for custom hauling rates (KDA & LUSO, 2022). Distance to the mill from the elevator was estimated as 240 km (Anderson et al., 2014) which is also near the maximum distance from the furthest wheat-growing area of Kansas to Stafford County Flour Mills. Domestic wheat transport has been reported near 50% by truck and 50% by rail since 2012 (Henderson et al., 2023), and thus transport of wheat from elevator to mill and flour from mill to bakery was assumed to use this mode split. Wheat flour transportation distance to a large bakery was determined similar to Meisterling at 2,000 km (Meisterling et al., 2009). This covers the distance from Wichita, KS to either New York City, NY or Los Angeles, CA, which are the two most populated cities in the U.S. Bread distribution to retail used coefficients from Avlani & Chancellor (1977). Transportation of bread to the consumer's home for consumption was estimated using allocation methods and travel distances similar to literature (Bandekar et al.,

2022; Table B.8). In most cases, these assumptions covered the maximum distance possibilities to prevent underestimation of transportation impacts.

2.2.6.2 Energy and Carbon Balance

Bread energy output was determined using energy values for each of the ingredients in the bread recipe from the FoodData Central databases (USDA ARS, 2019). The products from the database that were selected, and their respective energy coefficients are shown in Table B.9. The experimental bread recipe was used as a standard for the ratios of ingredients to eliminate differences that might occur in recipes among bakeries. Thus, net energy was calculated as energy output from bread minus energy input from cradle to grave and adjusted relative to the functional unit.

Carbon balance calculations used a combination of literature and experimental data to determine carbon sequestration and carbon removal during the wheat production phase. Total carbon assimilation was determined according to Bolinder et al. (2007) and modified using our measured data according to Eq. 2.1:

Equation 2.1. *Total Carbon Assimilation = CP + CS + CR + CE*

where CP is the plant C in product (grain), CS is the plant C in the stover, CR is the plant C in roots, and CE is the plant C from root exudates. Carbon contained in the grain (CP) and stover (CS) was measured in the experimental units, here calculated by multiplying either grain yield or stover yield by their respective measured carbon contents. Root biomass was determined based on a root:shoot ratio of 0.257, a ratio measured in commercial winter wheat genotypes in the study region (Awad et al., 2018) and similar to the IPCC (2006) suggestion of 0.23:1 for winter wheat. Root carbon content was assumed to be similar to stover; thus, total root carbon (CR) was calculated by multiplying root biomass by stover carbon content. Extra-root carbon (CE)

followed calculations by Bolinder et al. (2007) which assumes that an equivalent of 65% of total root carbon is released to the rhizosphere as CE. Carbon inputs to the soil were thus calculated as $CS + CR + CE$ and carbon removal from the system as CP. Carbon sequestration was then calculated following Yang et al. (2023):

Equation 2.2. $Carbon\ sequestration = 0.0767 \times Carbon\ inputs + 0.2548$

where carbon inputs are equal to $CS + CR + CE$ from Equation 2.1. This relationship with carbon sequestration is similar to other relationships shown in literature (Kong et al., 2005).

2.2.6.3 Study Omissions

Although wheat milling and other processes include byproducts with other uses (e.g., biofuel, animal feed), only those processes relevant to wheat bread were considered in the current analyses since the majority of these processes contribute to bread production (i.e. 74-76%; Pagani et al., 2014). Therefore, 100 percent of the energy and emissions associated with wheat production, milling, and baking were allocated to wheat, flour, and bread, respectively.

Capital goods related to farming, transportation, milling, and baking machinery production were also excluded from the study. Consumer use and waste were assumed to be consistent regardless of the management intensity, and therefore were omitted. Energy and emissions associated with human labor are negligible (<2% contribution to total) and therefore disregarded from the study (Grassini & Cassman, 2012; Nadi et al., 2022).

As previously mentioned, future research could expand this life cycle assessment to include several other impact categories, such as eutrophication from nitrogen leaching and phosphorus runoff, and freshwater ecotoxicity from the use of pesticides and micronutrients, etc. While these other categories are important, the current study focused on the potential increase in food production, global warming potential, and net energy use, which are arguably the most

important impact categories that have been considered in industry and policy amid recent concerns related to feeding a growing global population while mitigating the drivers of climate change.

2.2.7 Statistical analyses

Analysis of variance (ANOVA) was conducted to determine the effect of management intensity on bread yield, GWP, and net energy. We considered management intensity as a fixed effect; and region, environment (site-year combination) nested within region, and genotype nested within region as random effects. With 23 site-years, treating environment as a random effect is justified as the evaluated conditions represent a random selection of environments that could occur in each of the two wheat growing regions of the Kansas, and allows for projection of results to a broader inference space (Moore & Dixon, 2015). In addition, this analysis assumes that the genotypes evaluated represent a random selection of available genotypes adapted for each of the regions. Linear regression was used to compare management intensity effects on grain yield, protein content, carbon sequestration potential, and bread yield relationships. Since the LCA output data did not follow linear trends, non-linear regression was used to display the inverse exponential trends of GWP, energy input, and net energy relationships with bread yield and linear regression was used for net GWP relationship with bread yield. The analysis was conducted using R Studio software (RStudio Team, 2020) using the package “lme4” (Bates et al., 2015) and plots were created using the package “ggplot2” (Wickham, 2016).

2.3 Results

2.3.1 Increases in grain production, nutrition, and carbon sequestration through sustainable intensification

Intensifying wheat management increased grain yield from 3.3 to 4.2 Mg ha⁻¹ across all sources of variation (Figure 2.3A) and, depending on environment, yield increases ranged from 0 to 2.8 Mg ha⁻¹ (Figure B.1). When yield was plotted against average yield, similar slopes were observed indicating that yield increases were constant regardless of the yield environment. Grain protein content, however, experienced decreases in slope and increases in y-intercepts with increased management when plotted against the average, suggesting that protein increases from management were greater in low protein (i.e., high yielding) environments (Figure 2.3B). Although higher yields related negatively with grain protein content within management class (slope < -0.39 % Mg⁻¹; p < 0.001), the increase in grain yield led by management was accompanied by increases in grain protein content that, across all sources of variation averaged 12.0 in the low and 12.9 % in the top treatment (Figure 2.3C). Also, protein content became progressively more predictable based on grain yield with increases in management intensification (R² increasing from 0.08 to 0.42). The concomitant increase in grain yield and protein resulted in greater bread yield (Figure 2.3D), which also experienced similar slopes when the yield of each treatment was plotted against the average management (Figure 2.3E). Bread yield ranged from an average 3.5 to 4.0 Mg ha⁻¹ in the low and standard managements and from 4.5 to 4.6 Mg ha⁻¹ in the high and top management intensities. Since bread yield did not increase from the high to the top management intensity (Inset, Figure 2.3F), the remaining manuscript will focus on specific comparisons between the average treatment, representing current conditions; and the high treatment, representing a reasonable level of management

intensification. We also note that higher yielding conditions as function of environmental and managerial variations resulted in more residue return to the soil (range: ~ 1 to 12.5 Mg ha^{-1} ; Figure B.2), consequently associating with higher C sequestration potential, which averaged 0.58 and 0.63 Mg ha^{-1} in low and average treatments and increased to 0.66 to 0.68 Mg ha^{-1} in high and top treatments (Figure 2.3F).

2.3.2 Global warming potential and energy use of intensive wheat management

Within the wheat production phase, GWP and energy input on an area basis increased with increases from low management intensity (Figure B.3). The GWP in the average input treatment was $1020 \text{ kg-CO}_2\text{e ha}^{-1}$ and increased to $1470 \text{ kg-CO}_2\text{e ha}^{-1}$ in the high treatment (a 1.4-fold increase), while energy input was 6.2 GJ ha^{-1} and increased to 9.0 GJ ha^{-1} in the high treatment (a 1.5-fold increase). When carbon sequestration potential was accounted for, the wheat production phase was a net carbon sink, averaging $2,288$ to $2,371 \text{ kg CO}_2\text{e ha}^{-1}$ sequestration in the average and high treatments. The relative increases in GWP and energy input were alleviated when these variables were yield-scaled since high- and top-management had greater grain yields. Yield-scaled GWP increased from 275 to $358 \text{ g-CO}_2\text{e per kg of bread}$ from the average to the high management treatments (a 1.3-fold increase) and energy inputs increased from 1.7 to $2.2 \text{ MJ per kg-bread}$, representing a 1.3-fold increase (Figure 2.4).

The impacts of management intensity on GWP and energy inputs depended on agricultural inputs. For example, yield-scaled diesel GWP decreased from $64 \text{ g-CO}_2\text{e}$ in the low to $56 \text{ g-CO}_2\text{e per kg of bread}$ in the average management, remaining steady at 56 - $57 \text{ g-CO}_2\text{e per kg of bread}$ with further management intensification. These decreases in the contribution of diesel to total yield-scaled GWP (and energy input) were still observed when actual emissions remained stable. The relative contribution of seed and pesticide impacts also declined with more

intensive management despite constant or increased actual emissions or energy input (e.g., from 3.8% and 2.2% in the average to 3.0% and 1.7% in the high treatment). Conversely, the impacts of fertility, especially nitrogen fertilizer, increased with increases in management intensification. Energy inputs from nitrogen fertilizer increased by 1.4-fold in the high management compared to average, resulting in increased contribution to total energy consumption from 53% to 56%. Nitrogen was also the greatest contributor to GWP either through fertilizer production or nitrous oxide field emissions, accounting for 57-76% of all GHG emissions associated with the wheat production phase.

While differences in GWP and energy input existed as function of management intensity in the wheat production phase, other phases had notable impacts within the bread product system (Figure 2.5). The wheat production phase only accounted for about 22% of total GHG emissions with average intensity of management, compared to 42% and 28% contributions from baking and transportation, respectively. While the contributions from the wheat production phase to total bread footprint increased with each increase in management intensity, it still only represented 26% of total GHG emissions in the high intensity. In general, increasing management intensity reduced the percent contribution to total GWP for both baking and transportation phases while actual emissions remained constant. In addition, processing and milling activities had minimal impacts on GWP, but accounted for 15-17% of energy inputs.

Management intensity also impacted GWP and energy input when considering all processes associated within the bread product system (Figure 2.5). Total emissions on an area basis ranged from 5.1-6.1 Mg-CO₂e ha⁻¹ from the average to the high management intensities, while energy inputs followed similar increasing trends with increases by 1.2-fold (Figure B.4). When scaled by bread yield, the increase in GWP and energy input in each step of intensification

were lower, ranging from 1.30-1.38 kg-CO₂e and 15.46-15.95 MJ per kg-bread between the average and high managements (Figure 2.5). Carbon sequestration and bread energy output ranged from 0.55-0.63 kg-CO₂e and 11.69-11.80 MJ per kg-bread (Figure 2.5), causing a reduction in net GWP ranging from 1.6- to 2.1-fold while net energy output ranged from -3.2 to -4.7 MJ per kg-bread (Table B.11).

Across all sources of variation, GWP related negatively with bread yield (Figure 2.6A). These negative relationships were clearly separated by management; however, the difference among management intensities diminished as bread yield increased, indicating that even at greater management intensities, similar GWP to less intensive management can be achieved contingent upon greater bread yield. For example, a GWP of 1.2 kg-CO₂e per kg of bread can be achieved in all four management intensities at different levels of bread yield (i.e., low, ~2000 kg ha⁻¹; average, ~3500 kg ha⁻¹; high, ~5500 kg ha⁻¹, and top ~7000 kg ha⁻¹). Although not as clearly defined, energy input per unit of bread (Figure 2.6B) followed similar trends as GWP with a negative relationship with bread yield that diminished as bread yield increased: Highest yield-scaled energy inputs were between ~17-18 MJ kg-bread⁻¹ for the high management and 15-16 MJ kg-bread⁻¹ for average treatment, and these differences decreased to 13.5-15 MJ kg-bread⁻¹ as bread yield increased.

The negative effects of GWP and energy inputs were reduced when carbon sequestration and bread energy output were accounted for (Figure 2.6C, D). While the resulting net GWP and net energy output were considerably lower than their respective totals, they did not follow the same negative relationship with bread yield. For net GWP, the relationship with bread yield was positive at low management intensity and became neutral and negative with increases in management intensity. Here, differences in management were greatest at low bread yield where

net GWP ranged from ~ 0.2 - 1.0 kg CO₂e kg-bread⁻¹, while increases in bread yield made net GWP more similar amongst treatments (ranging ~ 0.5 - 0.8 kg-CO₂e kg-bread⁻¹). Net energy showed a positive relationship with bread yield but increases diminished as bread yield increased. Even with carbon sequestration and bread energy output included, net emissions remained positive and net energy output was negative.

2.4 Discussion

Field experiments replicating the typical management adopted in commercial winter wheat fields across a wide range of environments coupled with milling and baking laboratory analyses and life cycle assessment revealed the potential for increased bread production and its associated environmental footprint related to global warming potential and energy balance.

2.4.1 Grain yield, grain protein content, and bread yield

The protein content dilution as function of grain yield increases is well documented and confirmed in this study (Barneix, 2007). However, we note that this dilution occurred within management intensity. When comparing across managements, grain protein content increased remarkably with increased intensity, showing promise that high yield and high grain protein content can be achieved. These results are especially impactful for the prospect of producing more nutritious food. Using the state of Kansas as an example, the 10-year averages of yield and protein content are 2.9 Mg ha⁻¹ and 11.8% across 3.2 million hectares cultivated to winter wheat (USDA-NASS, 2023), resulting in 1.1 million Mg of protein exports. Upscaling the findings of the current work, there is a potential to increase wheat grain yield in 1.13-fold and grain protein in 1.03-fold from average to high, resulting in 1.3 million Mg of protein exported.

These concomitant increases in grain yield and protein content increased bread yield. Increases in grain yield and related increases in bread yield are mechanic and function of flour

yield, simply by having more material to be processed into flour. Flour extraction is also positively correlated with protein content, which could have played a role in increased flour yields (Rozbicki et al., 2015). Likewise, increases in protein content relate to increases in bread yield because of its positive effect on farinograph water absorption (Sapirstein et al., 2018), which then results in additional water needed to reach the desired dough consistency (Linlaud et al., 2009). Therefore, higher water absorptions increase bread yield (Dencic et al., 2007; Schönhofen et al., 2017), the positive effects of higher water absorption are also reflected in increased loaf volume (Aydoğar et al., 2015) and other quality characteristics (Mudgil et al., 2016).

2.4.2 Environmental footprint of wheat production

The range in yield-scaled GWP measured in the current study (0.19 to 0.44 kg-CO₂e per kg-bread) falls within values from other wheat LCAs (Andersson & Ohlsson, 1999; Goucher et al., 2017; Meisterling et al., 2009) and just below the average found across European countries (Achten & Van Acker, 2016). Similarly, energy inputs associated with wheat production from our study were comparable to previous literature (Khan & Latif, 2010; Meisterling et al., 2009) and again just below estimates for European countries (Achten & Van Acker, 2016).

Increases in bread yield were not enough to offset the increases in GWP and energy consumption that resulted from increased inputs when carbon sequestration was not accounted for (Figure 2.5). Therefore, these results lead us to partially reject our central hypothesis that certain combinations of management practices would lead to increased food production at a similar or decreased GWP. This could partially be explained by the design of this study, since the exact same four management practices were tested at all environments within a region regardless of environmental conditions. Previous evidence suggested that the lowest yield-scaled GWP for

wheat was attained at a yield reduction relative to the highest yield at a given site of 9% (Linguist et al., 2012). Perhaps the four strategies that we evaluated did not allow us to assess a treatment attaining such yield reduction, which would have reflected an intensity somewhere between the average and high treatments. Furthermore, these four contrasting groups of management intensity naturally led to large differences in GWP that were not offset by increases in yield, with larger differences in lower yielding environments. In real-world situations, producers would not adopt the same management across years or fields, adjusting their management as function of weather conditions (e.g., Cruppe et al., 2021). Perhaps a different data structure (i.e., one collected via on-farm surveys) could increase the range of management strategies evaluated and help to identify opportunities for high net energy yield with lower GWP (e.g., Grassini and Cassman, 2012).

Among the management factors leading to increased GWP, yield-scaled impacts of fertility increased substantially as management intensified, meaning that the yield gain resulting from these additional inputs was not enough to negate them. These results may partially be explained by the typical diminishing returns in grain yield response to increasing nitrogen rates in which higher rates lead to sequentially lower yield increases (Lollato et al., 2019b). The effects of nitrogen were specifically notable with GWP which is consistent with other studies in which nitrous oxide emissions that are function of N fertilizer drove the majority of the GWP of greenhouse gas emissions for wheat (Linguist et al., 2012) and where nitrogen field emissions contributed a large proportion towards total wheat production emissions (Kim et al., 2009; Meisterling et al., 2009). However, a previous meta-analysis suggested that wheat yield-scaled GWP was fairly irresponsive to increases in N rates at the low N range but were large when nitrogen was applied at high rates (Linguist et al., 2012). We did not see a constant GWP phase

in our data, perhaps because nitrogen was not the single input being modified between treatments. Higher nitrogen use efficiencies can potentially help alleviate yield-scaled emissions (Van Groenigen et al., 2010), which can be achieved through agronomic management and genotype selection (Fageria & Baligar, 2005; Hawkesford and Griffiths, 2019; Gaju et al., 2011). Outside of field emissions, chemical nitrogen fertilizer and fuel usage were the greatest contributors to both GWP and energy inputs in wheat production (Taghavifar & Mardani, 2015). Although GWP and energy input increased with higher management intensity, we note that the highest quantity of energy input was 2.8 MJ per kg of grain, which is considerably lower than literature values for wheat energy output (i.e., 14.7 MJ per kg of grain; Ghasemi-Mobtaker et al., 2022; Gökdoğan & SeviM, 2016). This mismatch indicates that the negative net energy output of bread was likely more driven by phases of the bread production system other than wheat production – even at high energy inputs at the wheat production phase.

2.4.3 Environmental impacts of the bread product system

Total GWP of the bread system ranged from 1.22-1.46 kg-CO₂e kg-bread⁻¹, which is consistent with some studies (Espinoza-Orias et al., 2011; Kulak et al., 2015) but higher than other estimates (Andersson & Ohlsson, 1999; Goucher et al., 2017). Some of this could be attributed to our transportation assumptions, which were higher than some studies in order to prevent underestimation due to its high uncertainty (i.e., in reality, this differs from field to field). Energy inputs were also consistent with literature, falling within the range found by Andersson and Ohlsson (1999) of 12-22 MJ kg-bread⁻¹, encompassing the value for ‘average’ bread from Europe (Niero et al., 2015; Notarnicola et al., 2017), and just higher than values found in other studies (Carlsson-Kanyama et al., 2003).

When considering the whole bread product system, GWP and energy inputs were partially driven by wheat production (16-31%), baking (37-45%), and transportation (25-30%) phases. In this context, baking was the greatest contributor to GWP and energy input in all scenarios. At an average of 7.13 MJ kg-bread⁻¹, baking energy inputs were slightly lower than the 8.6 MJ kg-bread⁻¹ (without flour contributions) reported by Nadi et al. (2022). Other studies report lower values for baking energy; however, many of these studies report on a dough weight basis or do not consider the manufacture of the energy source (Le-bail et al., 2010). Nadi et al. (2022) reported natural gas as the fuel used in baking with the highest source of energy and emissions besides flour production, similar to the study we derived our energy coefficients from (Avlani and Chancellor, 1977). Therefore, opportunities exist to decrease the impacts of bread production through more efficient use of natural gas or a switch to other energy sources with lesser impacts in the baking process, which were beyond the scope of the current work.

We demonstrated that GWP estimates of wheat – both at the production phase or across the bread system – can change dramatically depending on whether calculations account for carbon sequestration. Very few agricultural studies consider carbon sequestration due to ambiguity in estimation procedures (Goglio et al., 2015), but its potential to mitigate the effects of GHG emissions highlight the importance of its inclusion in LCA (Lal, 2003). This is especially important for wheat – a crop that has consistently acted as a carbon sink in detailed carbon balance/flux studies that reported a similar range in C sequestration potential than those estimated based on our modeling effort (e.g., Bajgain et al., 2018; Gan et al., 2011, 2014; Veeck et al., 2022; Wagle et al., 2019, 2021). In our study, sequestration had a large effect in reducing emissions, accounting for up to 0.63 CO₂e kg-bread⁻¹ reduction. These estimations also indicate net positive emissions when only considering the wheat production phase (0.11 to 0.44 kg-CO₂e

ha⁻¹), and changes in the direction of the relationship between bread yield and net GWP (from positive in low management to negative in high management) when considering the entire bread production system. While considerations of carbon sequestration were not enough to offset total emissions of the bread product system despite significant reductions in net GWP, the net GWP of the four management systems seem to converge at bread yield values greater than ~6,000 kg ha⁻¹ (Figure 2.6C) – partially supporting our hypothesis that management practices combinations can lead to greater food production with similar environmental footprint, at least when carbon sequestration is considered.

Net energy balance has been widely used in studies involving biofuels (Mayer et al., 2020) and in some crop production studies (Grassini and Cassman, 2012); however, it is not as common in bread or other food from a system perspective. Since the energy requirements for food processing and packaging are generally higher than the caloric energy value of the food product itself (Heller & Keoleian, 2003), net energy calculations allow comparisons of systems in relation to their value for human consumption. In our study, even though bread energy output was near 11.8 MJ kg-bread⁻¹, mean net energy was still negative indicating that energy inputs were greater than energy outputs. However, the magnitude that bread energy outputs did offset inputs indicates that there is potential to achieve a net-zero energy balance, partially supporting our central hypothesis.

2.4.4 Implications for sustainable intensification of wheat production

With the need to increase global food production and food quality on limited land devoted to agriculture while minimizing environmental impacts, our study shows promising prospects for successful sustainable intensification. Even while not the greatest contributor to GWP and energy input of the entire bread system, modulation of management within the wheat

production phase presents an opportunity to sustainably increase food production. The production phase itself also seems to be a net carbon sink irrespective of management practice adopted; thus, wheat fits well in the scope of feeding a growing global population while mitigating drivers of climate change. While low-input management has a lower maximum environmental impact, the consequent decrease in production causes concern for supply to the food system. This is consistent with previous research who suggested the need to focus on yield-scaled GWP rather than on an area basis since the latter can lead to low yielding management practices (Linguist et al., 2012). In addition, achieving higher bread yields with low-input management can lead to negative nutrient balances that are unsustainable and lead to many other environmental concerns (Koritschoner et al., 2023), including the potential to cause higher net GWP (Figure 2.6C). Meanwhile, if production practices remain constant (i.e., average management), improvement is still possible to reduce management-induced yield-gaps to yield levels in which net GWP is no longer affected by yield. Increasing intensity to high-input management showed potential to narrow the yield-gap, but it predominantly came with additional environmental costs, particularly in low-yielding environments. With additional inputs, carbon sequestration becomes high enough due to greater residue production and associated carbon return to soil (Figure 2.3F, B.2) so that GWP negatively related with bread yield, even without increases in yield from high intensity.

Our study suggests that the greatest concerns associated with management intensification would be environmental impacts under low bread yielding conditions (i.e. $\sim 2000 \text{ kg ha}^{-1}$), which is also where the greatest differences between GWP, energy input, net GWP, and net energy output occur. These differences diminish as bread yield increases (e.g. ~ 1.4 -fold difference at $2000 \text{ kg-bread ha}^{-1}$ to ~ 1.2 -fold difference at $6000 \text{ kg-bread ha}^{-1}$), presenting opportunity for

additional research to improve the predictive power for determining when these low-yield environments will occur to better guide management adoption at the field level for both food and environmental securities (e.g., Chenu et al., 2011; Couëdel et al., 2021). In this way, management could be modulated to reduce environmental impacts when these low-yield environments are likely. Likewise, higher confidence that high yields or increased higher carbon sequestration can be achieved, increased inputs would be warranted, benefiting both the producer and the environment.

2.4.5 Limitations of the current study

Similar to any study, the current study has limitations perhaps especially regarding the calculations of carbon sequestration. Carbon sequestration is highly dependent on climate and weather conditions, as higher temperatures and rainfall promote carbon breakdown and release from the soil (Lal, 2004; Post and Kwon, 2000). In addition, C sequestration is a long-term process that is dependent on other soil conditions, making direct calculations difficult. As a result, models that calculate carbon sequestration often come with a high degree of uncertainty. Nonetheless, even though carbon sequestration is environment-dependent, its calculation is still useful for making comparisons between treatments tested in the same environments and the results our modeling effort proposed have similar magnitude to those from detailed carbon flux studies (e.g., Bajgain et al., 2018; Gan et al., 2011, 2014; Veeck et al., 2022; Wagle et al., 2019, 2021), supporting our claims. Similarly, field emissions of nitrous oxide emissions are also highly influenced by environmental conditions. Here we used international standards from IPCC (2006); however, better models for emission estimation could reduce the uncertainty of these calculations (e.g., Grassini and Cassman, 2012). Another important limitation of our study includes assumptions regarding milling and baking coefficients, since we used the schematic

representation for these processes from a relatively old study (Avlani and Chancellor, 1977). However, we updated energy and emission coefficients for energy and fuel manufacture to attempt to overcome this issue.

Future research should focus on the improvement of estimations for processes within the bread product chain that are difficult to measure. In the wheat production phase, this can include carbon sequestration potential and nitrous oxide field emissions. In other phases, transportation assumptions could be refined, and the milling and baking process information could be updated for future LCA or sustainability studies. In addition, exploring other crops or foods in a similar context could be useful for comparisons and for scenario analysis to predict future trends in sustainability.

2.5 Conclusions

Life cycle assessment paired with replicated field studies and detailed laboratory analyses proved useful to identify avenues for sustainable intensification. Agricultural management influenced downstream processes; therefore, considering the entire system is important for quantifying the environmental impacts of management intensification. Here, a combination of yield and protein gains resulted in higher bread yield, lessening the magnitude of GWP and energy input increases. Although GWP and energy input increased when management intensity increased, carbon sequestration and energy output considerations greatly reduced these impacts for net GWP and net energy yield. We provided evidence for an opportunity to increase bread yield with minor increases in yield-scaled environmental impacts. Further technological and input use efficiency improvements could further reduce these impacts from the agricultural perspective, however improvement of other aspects of the bread product system – which were beyond the scope of this work but reflected the majority of GWP and energy input– could play a

significant role in decreased environmental impacts. This system-wide approach showed that collective progression of the members of the bread supply chain can result in successful sustainable intensification.

Table 2.1. Description of the 23 field experiments conducted during the 2020-21 and 2021-22 winter wheat growing seasons in Kansas, US. Soil information, environmental conditions, and dates of treatment activities for each study-site are provided.

Year	Region	Site Name	Soil Type	In-season Rainfall (mm)	Planting Date	Fertilizer 1 Date	Fertilizer 2 Date	Fungicide 1 Date	Fungicide 2 Date	Harvest Date
2020-21	Sub-Humid	Ashland Bottoms (1)	Belvue silt loam	858	14-Oct-20	9-Mar-21	5-Apr-21	9-Apr-21	10-May-21	23-Jun-21
		Ashland Bottoms (2)	Bismarckgrove-Kimo complex	899	13-Oct-20	9-Mar-21	5-Apr-21	12-Apr-21	12-May-21	27-Jun-21
		Belleville	Crete silt loam	553	5-Oct-20	10-Mar-21	6-Apr-21	13-Apr-21	18-May-21	1-Jul-21
		Hutchinson	Ost Loam	801	8-Oct-20	8-Mar-21	1-Apr-21	9-Apr-21	5-May-21	16-Jun-21
		Manhattan	Kahola silt loam	943	7-Oct-20	9-Mar-21	5-Apr-21	12-Apr-21	13-May-21	5-Jul-21
		Tipton	Harney silt loam	775	25- Oct-20*	10-Mar-21	6-Apr-21	13-Apr-21	24-May-21	21-Jul-21
	Semi-Arid	Colby	Keith silt loam	749	29-Sep-20	11-Mar-21	6-May-21	23-Apr-21	30-May-21	11-Jul-21
		Garden City	Ulysses silt loam	592	20-Sep-20	10-Mar-21	14-Apr-21	4-Apr-21	14-May-21	9-Jul-21
		Leoti	Richfield silt loam	626	25-Sep-20	10-Mar-21	14-Apr-21	14-Apr-21	26-May-21	12-Jul-21
		Norcatur	Holdrege silt loam	550	19-Oct-20	12-Mar-21	8-May-21	24-Apr-21	2-Jun-21	17-Jul-21
2021-22	Sub-Humid	Ashland Bottoms	Belvue silt loam	1115	12-Oct-21	16-Mar-22	12-Apr-22	26-Apr-22	11-May-22	29-Jun-22
		Belleville	Crete silt loam	761	7-Oct-21	16-Mar-22	14-Apr-22	2-May-22	18-May-22	11-Jul-22
		Hutchinson	Funmar-Taver loams	666	21-Oct-21	15-Mar-22	15-Apr-22	26-Apr-22	10-May-22	14-Jun-22
		Manhattan (1)	Kahola silt loam	1138	18-Oct-21	15-Mar-22	12-Apr-22	27-Apr-22	16-May-22	1-Jul-22
		Manhattan (2) Late	Kahola silt loam	1090	19-Nov-21	15-Mar-22	12-Apr-22	11-May-22	2-Jun-22	8-Jul-22
		Great Bend	Taver loam	506	20-Oct-21	16-Mar-22	21-Apr-22	25-Apr-22	14-May-22	20-Jun-22
		Solomon	Detroit silty clay loam	743	21-Oct-21	15-Mar-22	12-Apr-22	26-Apr-22	14-May-22	27-Jun-22
	Semi-Arid	Belleville	Crete silt loam	761	7-Oct-21	16-Mar-22	14-Apr-22	2-May-22	18-May-22	11-Jul-22
		Colby	Keith silt loam	275	12-Oct-21	3-Mar-22	4-May-22	26-Apr-22	28-May-22	11-July-22
		Garden City	Satanta silt loam	293	29-Sep-21	16-Mar-22	21-Apr-22	29-Apr-22	9-May-22	30-Jun-22
		Hays	Harney silt loam	427	28-Sep-21	16-Mar-22	21-Apr-22	25-Apr-22	6-May-22	23-Jun-22
		Leoti	Richfield silt loam	316	25-Sep-21	16-Mar-22	21-Apr-22	25-Apr-22	17-May-22	5-Jul-22
		Norcatur	Holdrege silt loam	296	8-Oct-21	3-Mar-22	4-May-22	27-Apr-22	1-Jun-22	22-July-22
*Estimated dates										

Table 2.2. Management level and frequency of adoption of different management practices evaluated in this study. Practices were developed from a survey of 656 fields grouped into low, average, high, and top yielding fields. Each treatment received different combinations of inputs at differing rates, based on producer practices in both climatic regions of Kansas.

	Sub-Humid Region of Kansas Previous crop: Soybean				Semi-Arid Region of Kansas Previous crop: Fallow			
Practice (unit ha ⁻¹)	Low	Average	High	Top	Low	Average	High	Top
Yield goal (Mg)	2.4	3.7	5.0	6.4	2.4	3.7	5.4	6.4
Seeding rate (seeds)	2,500,000	3,000,000	3,600,000	3,600,000	1,900,000	2,200,000	2,600,000	2,600,000
Nitrogen (kg N)	45	90	135	180	45	90	135	200
Phosphorus (kg P)	-	22	34	39	-	-	34	34
Sulfur (kg S)	-	11	11	22	-	-	11	22
Chloride (kg Cl)	-	17	17	17	-	-	-	-
Seed Treatment	-	Yes	Yes	Yes	-	-	Yes	Yes
Split N Application	-	-	Yes	Yes	-	-	Yes	Yes
Flag leaf Fungicide	-	-	Yes	Yes	-	-	Yes	Yes
Jointing Fungicide	-	-	-	Yes	-	-	-	Yes
Micronutrients	-	-	-	Yes	-	-	-	Yes

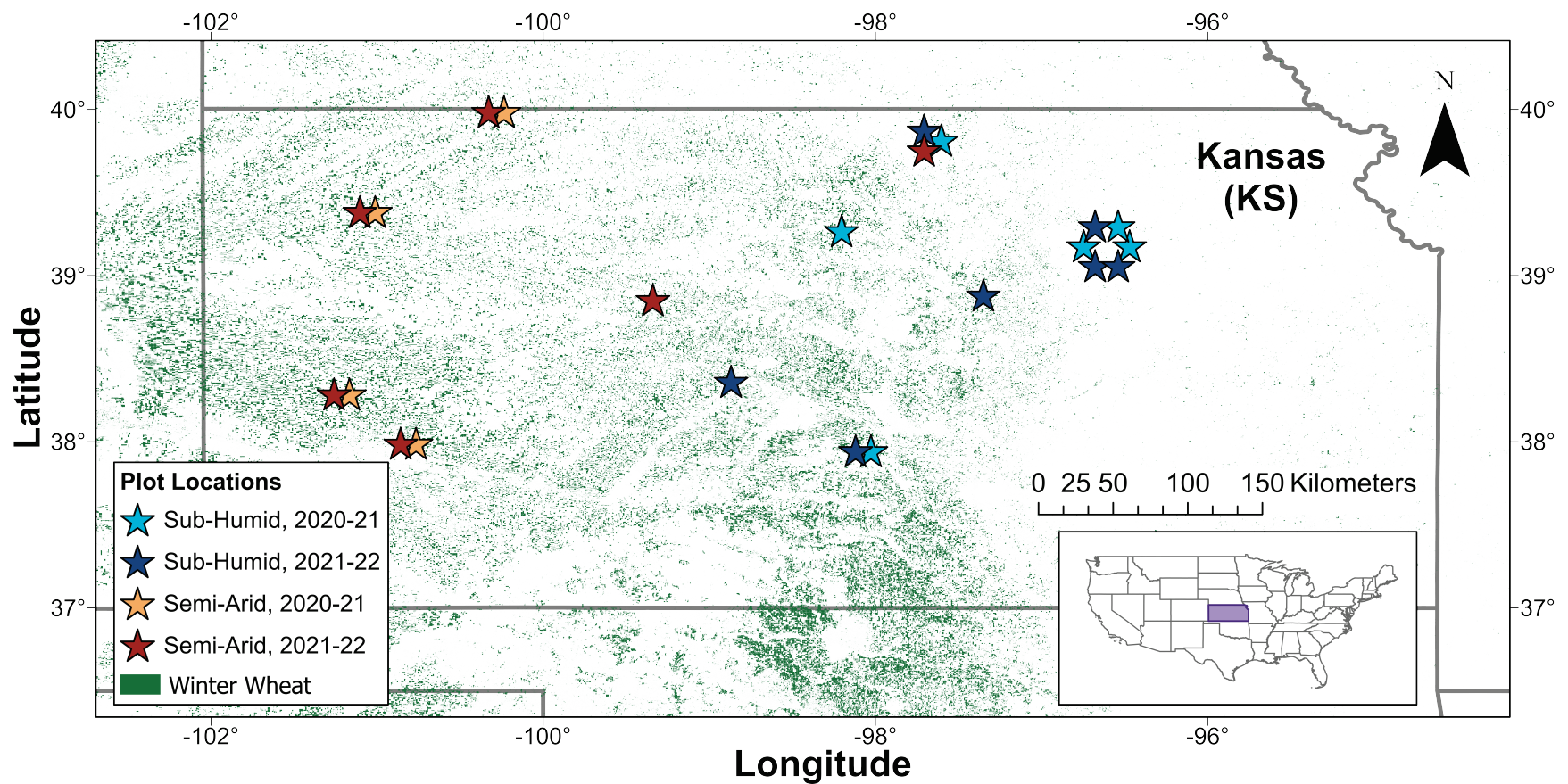


Figure 2.1. Winter wheat area (green raster) and experimental sites and years included in this study. Sites are divided in those established in sub-humid (blue) or the semi-arid (orange) regions. Inset map shows location of the study region within the continental US.

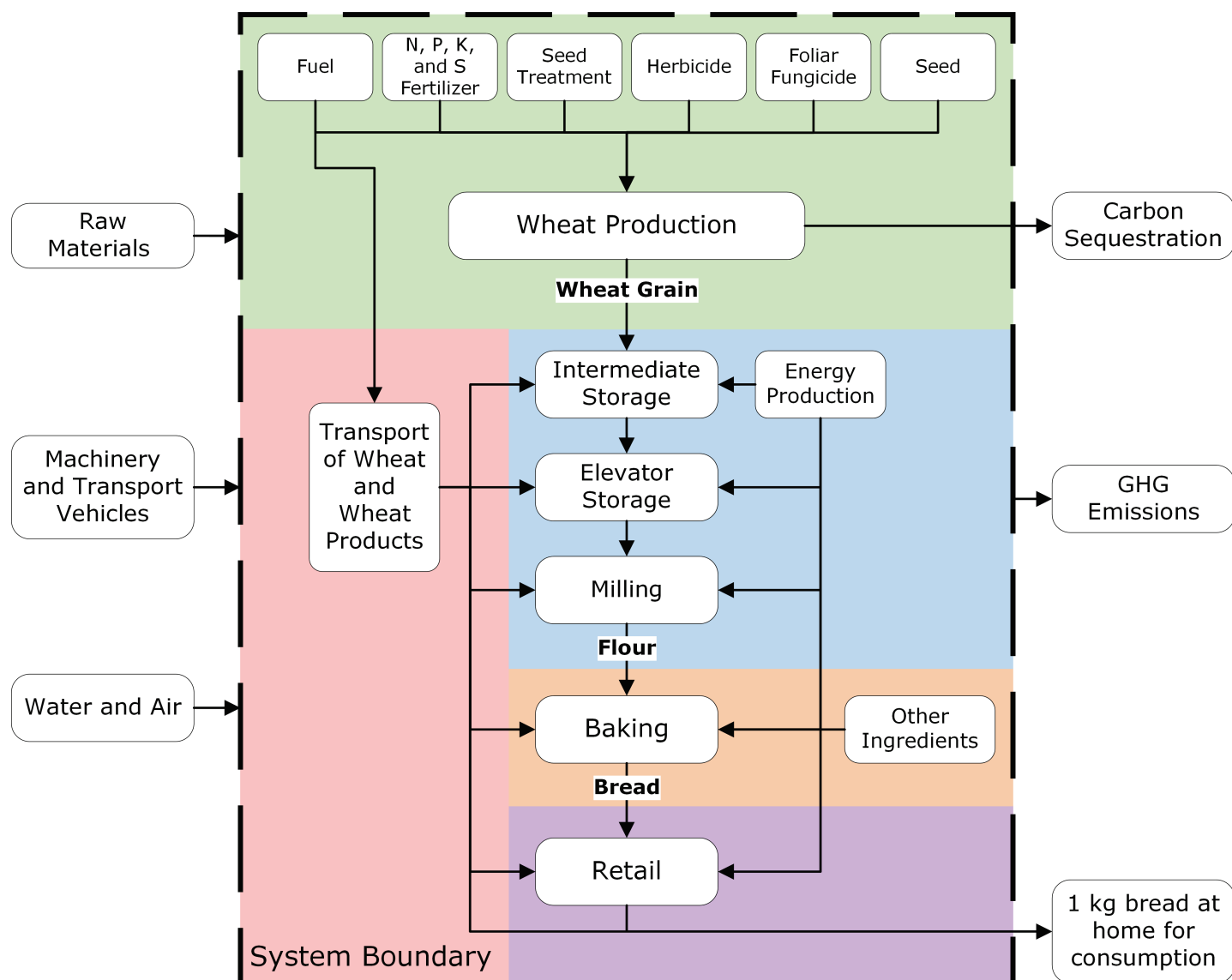


Figure 2.2. System boundaries of the current life cycle assessment, including study inputs, outputs, and their flows. Colors indicate processes categorized together for determining impact by phase of the bread product system.

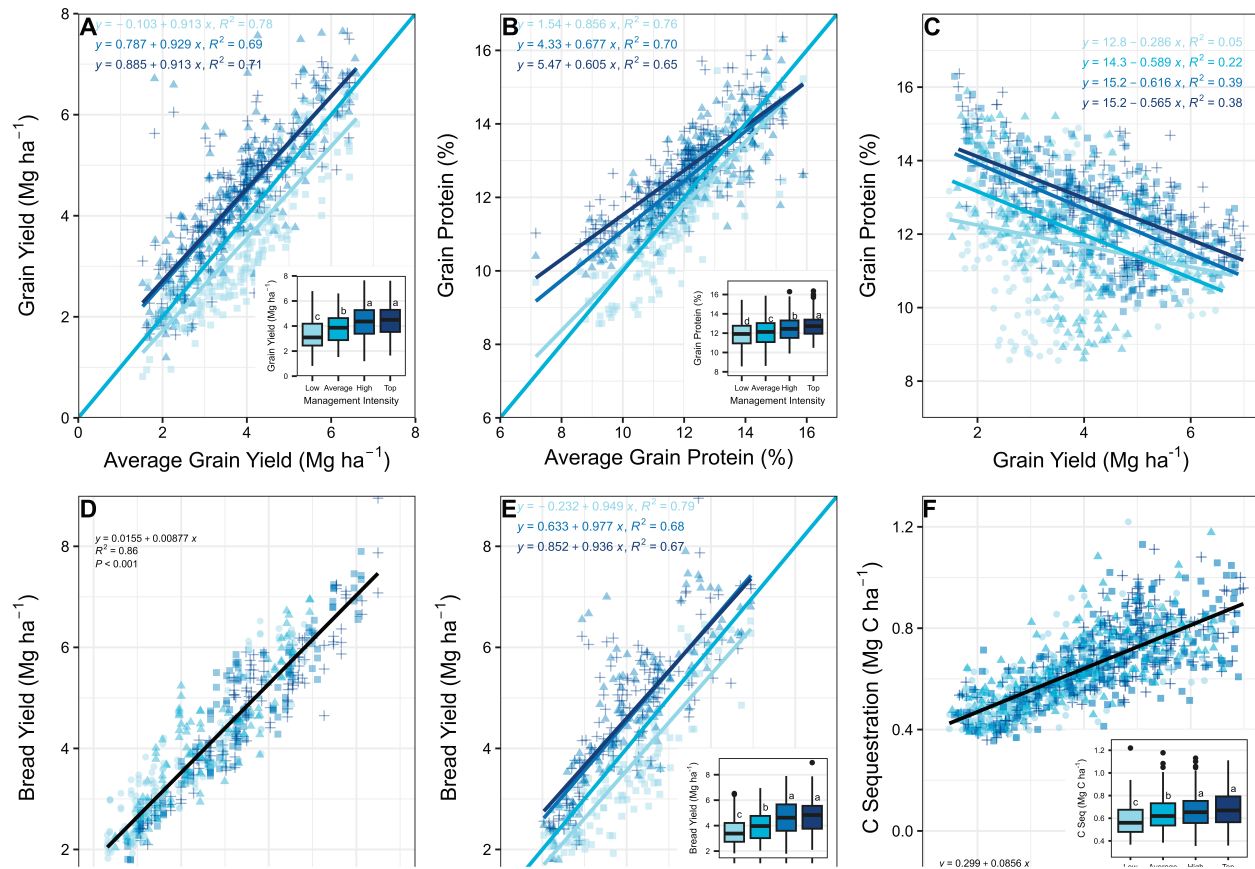


Figure 2.3. Grain yield (A) and grain protein (B) in the average management is shown in relation to other management intensities, while grain protein content relationship with grain yield is displayed as a function of management intensity (C). Bread yield showed a positive relationship with protein yield (D) calculated as the product between yield and protein content, while average intensity bread yield (E) is shown in relation to other management intensities. Carbon sequestration estimates are displayed as a function of grain yield across all sources of variation (F). Inset graphs show the distribution of grain yield (A), grain protein (B), bread yield (E), and carbon sequestration (F) resulting from each management intensity across all sources of variation. Letters denote statistical significance of means at the alpha <0.05 level.

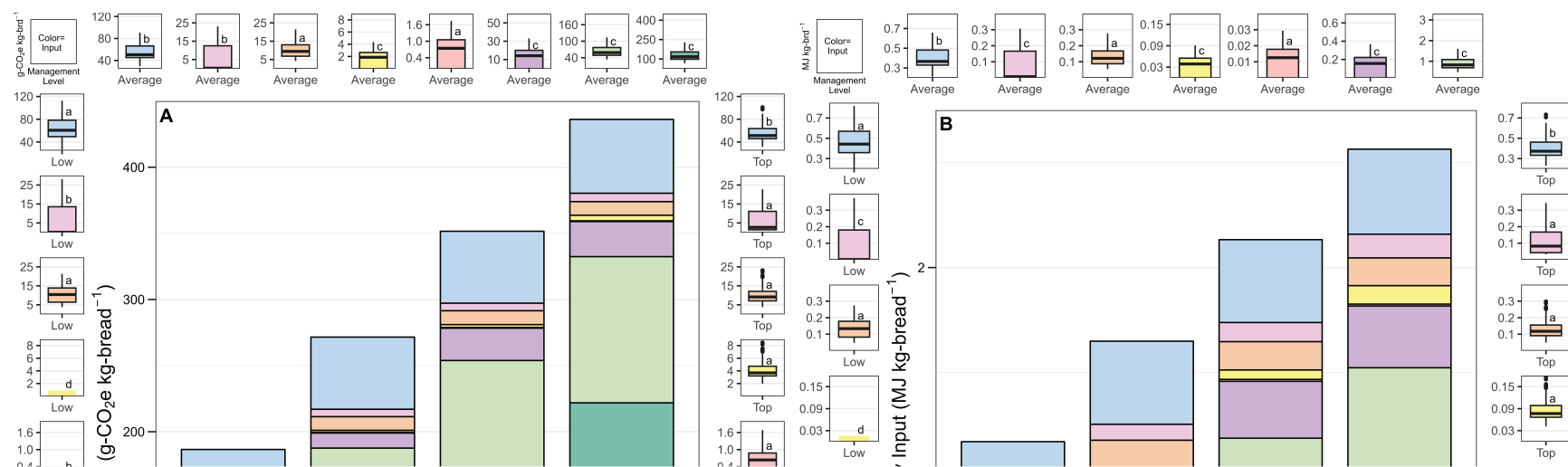


Figure 2.4. Agricultural input (color) contributions to GWP (A) and energy inputs (B) associated with the wheat production phase of the bread product system quantified per unit of bread produced and are factored by management intensity. Data distribution of each phase is indicated in the boxplots surrounding each graph, with letters statistical significance between management intensities at the $\alpha < 0.05$ level. For detailed statistical comparison among subgroups, please refer to Table B.10.

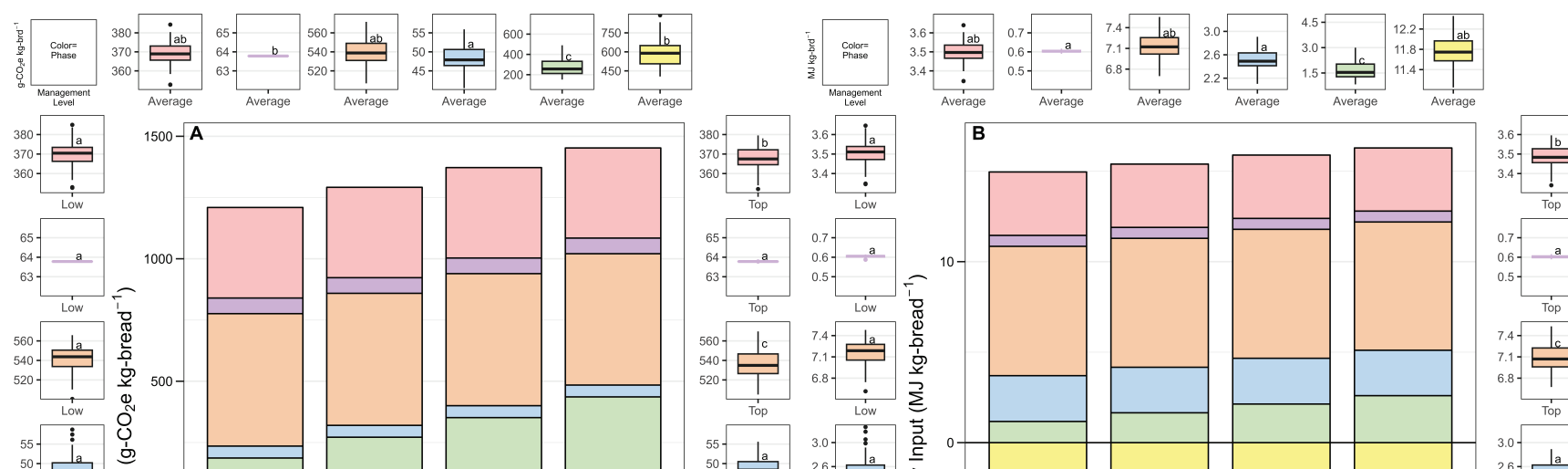


Figure 2.5. Contributions of each phase in the bread product system to (A) global warming potential (GWP) and (B) energy inputs per unit of bread produced and separated by management intensity. Data distribution of each phase is indicated in the boxplots surrounding each graph, with letters statistical significance at the alpha < 0.05 level. For detailed statistical comparison among subgroups, please refer to Table B.11.

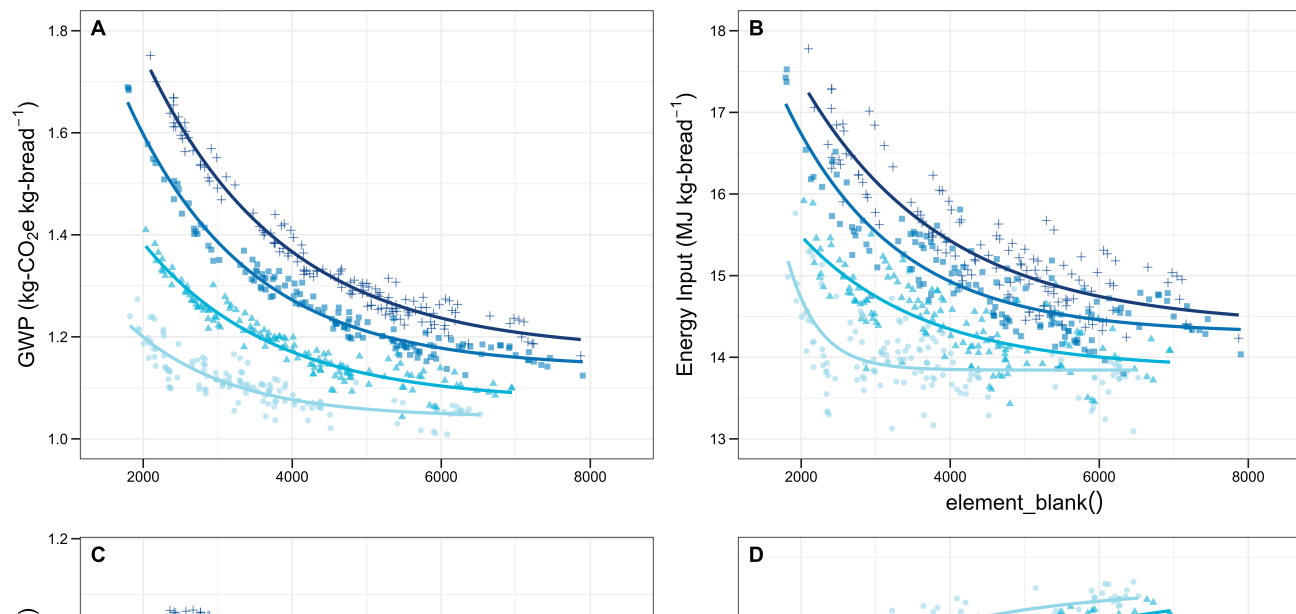


Figure 2.6. Relationship between bread yield and (A) yield-scaled global warming potential (GWP), (B) energy inputs, (C) net GWP, and (D) net energy output. Net GWP refers to GHG emissions less the equivalent of carbon sequestration, while net energy output is bread energy output minus energy inputs. Color shade and shapes denote intensity of management. Equations of fitted lines are given in Table B.12

References

- Achten, W. M. J., & Van Acker, K. (2016). EU-Average Impacts of Wheat Production: A Meta-Analysis of Life Cycle Assessments: EU-Average Impacts of Wheat Production. *Journal of Industrial Ecology*, 20(1), 132–144. <https://doi.org/10.1111/jiec.12278>
- Adler, P. R., Rau, B. M., & Roth, G. W. (2015). Sustainability of Corn Stover Harvest Strategies in Pennsylvania. *BioEnergy Research*, 8(3), 1310–1320. <https://doi.org/10.1007/s12155-015-9593-2>
- Aerni, P., Scholderer, J., & Ermen, D. (2011). How would Swiss consumers decide if they had freedom of choice? Evidence from a field study with organic, conventional and GM corn bread. *Food Policy*, 36(6), 830–838. <https://doi.org/10.1016/j.foodpol.2011.08.002>
- Afshar, R. K., & Dekamin, M. (2022). Sustainability assessment of corn production in conventional and conservation tillage systems. *Journal of Cleaner Production*, 351, 131508. <https://doi.org/10.1016/j.jclepro.2022.131508>
- Ahmad, A., Zoli, M., Latella, C., & Bacenetti, J. (2023). Rice cultivation and processing: Highlights from a life cycle thinking perspective. *Science of The Total Environment*, 871, 162079. <https://doi.org/10.1016/j.scitotenv.2023.162079>
- Alaoui, A., Barão, L., Ferreira, C. S. S., & Hessel, R. (2022). An Overview of Sustainability Assessment Frameworks in Agriculture. *Land*, 11(4), Article 4. <https://doi.org/10.3390/land11040537>
- Al-Saidi, M., 2023. Caught off guard and beaten: The Ukraine war and food security in the Middle East. *Frontiers in Nutrition*, 10, p.983346.
- Al-Saidi, M., 2023. Caught off guard and beaten: The Ukraine war and food security in the Middle East. *Frontiers in Nutrition*, 10, p.983346.
- American Farm Bureau Federation. (2022). Sustainability in Agriculture. American Farm Bureau Federation. <https://www.fb.org/land/sustainability>
- Anderson, E., Callahan, R., Colvin, T., McClure, C., O'Donoghue, M., & Powell-Palm, N. (2014). *Cashing in the Joules: The Economics of Energy Inputs in Dryland Wheat Farming*. https://landresources.montana.edu/archives/capstone/2014_Capstone_Wheat.pdf
- Andersson, K., & Ohlsson, T. (1999). Life cycle assessment of bread produced on different scales. *The International Journal of Life Cycle Assessment*, 4(1), 25–40. <https://doi.org/10.1007/BF02979392>
- Andrade, J.F., Mourtzinis, S., Edreira, J.I.R., Conley, S.P., Gaska, J., Kandel, H.J., Lindsey, L.E., Naeve, S., Nelson, S., Singh, M.P. and Thompson, L., 2022. Field validation of a farmer

- supplied data approach to close soybean yield gaps in the US North Central region. *Agricultural Systems*, 200, p.103434.
- Aoki, K., Akai, K., & Ujiie, K. (2017). A choice experiment to compare preferences for rice in Thailand and Japan: The impact of origin, sustainability, and taste. *Food Quality and Preference*, 56, 274–284. <https://doi.org/10.1016/j.foodqual.2016.03.001>
- Arnall, D.B., Mallarino, A.P., Ruark, M.D., Varvel, G.E., Solie, J.B., Stone, M.L., Mullock, J.L., Taylor, R.K. and Raun, W.R., 2013. Relationship between grain crop yield potential and nitrogen response. *Agronomy Journal*, 105(5), pp.1335-1344.
- Arulnathan, V., Heidari, M. D., Doyon, M., Li, E., & Pelletier, N. (2020). Farm-level decision support tools: A review of methodological choices and their consistency with principles of sustainability assessment. *Journal of Cleaner Production*, 256, 120410. <https://doi.org/10.1016/j.jclepro.2020.120410>
- ASA, (American Society of Agronomy). (2022). What is sustainable agronomy? Sustainability | American Society of Agronomy. <https://www.agronomy.org/about-agronomy/sustainability>
- Ashoori, D., Allahyari, M. S., & Damalas, C. A. (2017). Adoption of conservation farming practices for sustainable rice production among small-scale paddy farmers in northern Iran. *Paddy and Water Environment*, 15(2), 237–248. <https://doi.org/10.1007/s10333-016-0543-1>
- Avlani, P. K., & Chancellor, W. J. (1977). Energy Requirements for Wheat Production and Use in California. *Transactions of the ASAE*, 20(3), 0429–0437. <https://doi.org/10.13031/2013.35572>
- Awad, W., Byrne, P. F., Reid, S. D., Comas, L. H., & Haley, S. D. (2018). Great Plains Winter Wheat Varies for Root Length and Diameter under Drought Stress. *Agronomy Journal*, 110(1), 226–235. <https://doi.org/10.2134/agronj2017.07.0377>
- Aydoğan, S., Şahin, M., & Akçacık, A. (2015). Relationships between Farinograph Parameters and Bread Volume, Physicochemical Traits in Bread Wheat Flours. *Crop Science*, 3, 14–18.
- Azzari, G., Grassini, P., Edreira, J.I.R., Conley, S., Mourtzinis, S. and Lobell, D.B., 2019. Satellite mapping of tillage practices in the North Central US region from 2005 to 2016. *Remote Sensing of Environment*, 221, pp.417-429.
- Baccar, M., Bouaziz, A., Dugué, P., Gafsi, M., & Le Gal, P.-Y. (2019). The determining factors of farm sustainability in a context of growing agricultural intensification. *Agroecology and Sustainable Food Systems*, 43(4), 386–408. <https://doi.org/10.1080/21683565.2018.1489934>
- Bakht, J., Shafi, M., Jan, M. T., & Shah, Z. (2009). Influence of crop residue management, cropping system and N fertilizer on soil N and C dynamics and sustainable wheat

- (*Triticum aestivum* L.) production. *Soil and Tillage Research*, 104(2), 233–240.
<https://doi.org/10.1016/j.still.2009.02.006>
- Balboa, G.R., Archontoulis, S.V., Salvagiotti, F., Garcia, F.O., Stewart, W.M., Francisco, E., Prasad, P.V. and Ciampitti, I.A., 2019. A systems-level yield gap assessment of maize-soybean rotation under high-and low-management inputs in the Western US Corn Belt using APSIM. *Agricultural Systems*, 174, pp.145-154.
- Balmford, A., Amano, T., Bartlett, H., Chadwick, D., Collins, A., Edwards, D., Field, R., Garnsworthy, P., Green, R., Smith, P., Waters, H., Whitmore, A., Broom, D. M., Chara, J., Finch, T., Garnett, E., Gathorne-Hardy, A., Hernandez-Medrano, J., Herrero, M., ... Eisner, R. (2018). The environmental costs and benefits of high-yield farming. *Nature Sustainability*, 1(9), Article 9. <https://doi.org/10.1038/s41893-018-0138-5>
- Bana, R. C., Gupta, A. K., Bana, R. S., Shivay, Y. S., Bamboriya, S. D., Thakur, N. P., Puniya, R., Gupta, M., Jakhar, S. R., Kailash, Choudhary, R. S., Bochalya, R. S., Bajaya, T., Kumar, V., Kumar, P., & Choudhary, A. K. (2022). Zinc-Coated Urea for Enhanced Zinc Biofortification, Nitrogen Use Efficiency and Yield of Basmati Rice under Typical Fluvents. *Sustainability*, 14(1), Article 1. <https://doi.org/10.3390/su14010104>
- Bandekar, P. A., Putman, B., Thoma, G., & Matlock, M. (2022). Cradle-to-grave life cycle assessment of production and consumption of pulses in the United States. *Journal of Environmental Management*, 302, 114062.
<https://doi.org/10.1016/j.jenvman.2021.114062>
- Bare, J. (2011). TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy*, 13(5), 687–696. <https://doi.org/10.1007/s10098-010-0338-9>
- Barneix, A. J. (2007). Physiology and biochemistry of source-regulated protein accumulation in the wheat grain. *Journal of Plant Physiology*, 164(5), 581–590.
<https://doi.org/10.1016/j.jplph.2006.03.009>
- Barnes, A. P., & Thomson, S. G. (2014). Measuring progress towards sustainable intensification: How far can secondary data go? *Ecological Indicators*, 36, 213–220.
<https://doi.org/10.1016/j.ecolind.2013.07.001>
- Barrett, C. B. in Food Security and Sociopolitical Stability (ed. Barrett, C. B.) 1–34 (Oxford Univ. Press, 2013).
- Basiago, A. D. (1995). Methods of defining ‘sustainability.’ *Sustainable Development*, 3(3), 109–119. <https://doi.org/10.1002/sd.3460030302>
- Basosi, R., Spinelli, D., Fierro, A., & Jez, S. (2014). Mineral nitrogen fertilizers: Environmental impact of production and use. *Fertilizers: Components, Uses in Agriculture and Environmental Impacts*, 8.

- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1). <https://doi.org/10.18637/jss.v067.i01>
- Benidir, M., Ghoulane, F., Bousbia, A., & Belkheir, B. (2013). The use of a critical analysis of a multicriterion method (IDEA) for assessing the sustainability of sedentary sheep rearing systems in the Algerian steppe areas. *African Journal of Agricultural Research*, 8(9), 804–811. <https://doi.org/10.5897/AJAR12.1006>
- Bennett, E. M., Carpenter, S. R., & Caraco, N. F. (2001). Human Impact on Erovable Phosphorus and Eutrophication: A Global Perspective: Increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. *BioScience*, 51(3), 227–234. [https://doi.org/10.1641/0006-3568\(2001\)051\[0227:HIOEPA\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0227:HIOEPA]2.0.CO;2)
- Berbec, A. K., Feledyn-Szewczyk, B., Thalmann, C., Wyss, R., Grenz, J., Kopiński, J., Stalenga, J., & Radzikowski, P. (2018). Assessing the Sustainability Performance of Organic and Low-Input Conventional Farms from Eastern Poland with the RISE Indicator System. *Sustainability*, 10(6), Article 6. <https://doi.org/10.3390/su10061792>
- Berg, H., Ekman Söderholm, A., Söderström, A.-S., & Tam, N. T. (2017). Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. *Sustainability Science*, 12(1), 137–154. <https://doi.org/10.1007/s11625-016-0409-x>
- Berthoud, A., Maupu, P., Huet, C., & Poupart, A. (2011). Assessing freshwater ecotoxicity of agricultural products in life cycle assessment (LCA): A case study of wheat using French agricultural practices databases and USEtox model. *The International Journal of Life Cycle Assessment*, 16(8), 841. <https://doi.org/10.1007/s11367-011-0321-7>
- Biret, C., Buttard, C., Farny, M., Lisbona, D., Janekarnkij, P., Barbier, J.-M., & Chambon, B. (2019). Assessing sustainability of different forms of farm organization: Adaptation of IDEA method to rubber family farms in Thailand. *BASE*, 2, 74–87. <https://doi.org/10.25518/1780-4507.17622>
- Biswas, S., Hazra, G. C., Purakayastha, T. J., Saha, N., Mitran, T., Singha Roy, S., Basak, N., & Mandal, B. (2017). Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders. *Geoderma*, 292, 34–48. <https://doi.org/10.1016/j.geoderma.2017.01.003>
- Biswas, W. K., Graham, J., Kelly, K., & John, M. B. (2010). Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia – a life cycle assessment. *Journal of Cleaner Production*, 18(14), 1386–1392. <https://doi.org/10.1016/j.jclepro.2010.05.003>
- Boisset, K., Girardin, P., Guillaumin, A., Mouchet, C., Viaux, P., Zahm, F., & Vilain, L. (2008). La méthode IDEA: Indicateurs de durabilité des exploitations agricoles : guide d'utilisation.

- Bojanić, N., Fišteš, A., Rakić, D., Kolar, S., Ćurić, B., & Petrović, J. (2021). Study on the effects of smooth roll grinding conditions on reduction of wheat middlings using response surface methodology. *Journal of Food Science and Technology*, 58(4), 1430–1440. <https://doi.org/10.1007/s13197-020-04654-5>
- Bolinder, M. A., Janzen, H. H., Gregorich, E. G., Angers, D. A., & VandenBygaart, A. J. (2007). An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems & Environment*, 118(1), 29–42. <https://doi.org/10.1016/j.agee.2006.05.013>
- Bonisoli, L., Galdeano-Gómez, E., & Piedra-Muñoz, L. (2018). Deconstructing criteria and assessment tools to build agri-sustainability indicators and support farmers' decision-making process. *Journal of Cleaner Production*, 182, 1080–1094. <https://doi.org/10.1016/j.jclepro.2018.02.055>
- Bonisoli, L., Galdeano-Gómez, E., Piedra-Muñoz, L., & Pérez-Mesa, J. C. (2019). Benchmarking agri-food sustainability certifications: Evidences from applying SAFA in the Ecuadorian banana agri-system. *Journal of Cleaner Production*, 236, 117579. <https://doi.org/10.1016/j.jclepro.2019.07.054>
- Boone, L., Van Linden, V., De Meester, S., Vandecasteele, B., Muylle, H., Roldán-Ruiz, I., Nemecek, T., & Dewulf, J. (2016). Environmental life cycle assessment of grain maize production: An analysis of factors causing variability. *Science of The Total Environment*, 553, 551–564. <https://doi.org/10.1016/j.scitotenv.2016.02.089>
- Bramley, R.G.V. and Ouzman, J., 2019. Farmer attitudes to the use of sensors and automation in fertilizer decision-making: Nitrogen fertilization in the Australian grains sector. *Precision agriculture*, 20, pp.157-175.
- Brito, T., Fragoso, R., Marques, P., Fernandes-Silva, A., & Aranha, J. (2021). LCA of Soybean Supply Chain Produced in the State of Pará, Located in the Brazilian Amazon Biome. *Biology and Life Sciences Forum*, 3(1), Article 1. <https://doi.org/10.3390/IECAG2021-10072>
- Brodt, S., Kendall, A., Mohammadi, Y., Arslan, A., Yuan, J., Lee, I.-S., & Linquist, B. (2014). Life cycle greenhouse gas emissions in California rice production. *Field Crops Research*, 169, 89–98. <https://doi.org/10.1016/j.fcr.2014.09.007>
- Brookes, G., & Dinh, T. X. (2021). The impact of using genetically modified (GM) corn/maize in Vietnam: Results of the first farm-level survey. *GM Crops & Food*, 12(1), 71–83. <https://doi.org/10.1080/21645698.2020.1816800>
- Broom, D.M., 2017. Components of sustainable animal production and the use of silvopastoral systems. *Revista Brasileira de Zootecnia*, 46, pp.683-688.
- Brown, B. J., Hanson, M. E., Liverman, D. M., & Merideth, R. W. (1987). Global sustainability: Toward definition. *Environmental Management*, 11(6), 713–719. <https://doi.org/10.1007/BF01867238>

- Bueno, A. F., Panizzi, A. R., Hunt, T. E., Dourado, P. M., Pitta, R. M., & Gonçalves, J. (2021). Challenges for Adoption of Integrated Pest Management (IPM): The Soybean Example. *Neotropical Entomology*, 50(1), 5–20. <https://doi.org/10.1007/s13744-020-00792-9>
- Cammarata, M., Timpanaro, G., & Scuderi, A. (2021). Assessing Sustainability of Organic Livestock Farming in Sicily: A Case Study Using the FAO SAFA Framework. *Agriculture*, 11(3), Article 3. <https://doi.org/10.3390/agriculture11030274>
- Campbell, B. M., Vermeulen, S. J., Aggarwal, P. K., Maizeer-Dolloff, C., Girvetz, E., Loboguerrero, A. M., Ramirez-Villegas, J., Rosenstock, T., Sebastian, L., Thornton, P. K., & Wollenberg, E. (2016). Reducing risks to food security from climate change. *Global Food Security*, 11, 34–43. <https://doi.org/10.1016/j.gfs.2016.06.002>
- Campbell, G. M. (2007). Chapter 7 Roller Milling of Wheat. In A. D. Salman, M. Ghadiri, & M. J. Hounslow (Eds.), *Handbook of Powder Technology* (Vol. 12, pp. 383–419). Elsevier Science B.V. [https://doi.org/10.1016/S0167-3785\(07\)12010-8](https://doi.org/10.1016/S0167-3785(07)12010-8)
- Cappelli, A., & Cini, E. (2021). Challenges and Opportunities in Wheat Flour, Pasta, Bread, and Bakery Product Production Chains: A Systematic Review of Innovations and Improvement Strategies to Increase Sustainability, Productivity, and Product Quality. *Sustainability*, 13(5), Article 5. <https://doi.org/10.3390/su13052608>
- Cappelli, A., Oliva, N., & Cini, E. (2020). Stone milling versus roller milling: A systematic review of the effects on wheat flour quality, dough rheology, and bread characteristics. *Trends in Food Science & Technology*, 97, 147–155. <https://doi.org/10.1016/j.tifs.2020.01.008>
- Carlsson-Kanyama, A., Ekström, M. P., & Shanahan, H. (2003). Food and life cycle energy inputs: Consequences of diet and ways to increase efficiency. *Ecological Economics*, 44(2–3), 293–307. [https://doi.org/10.1016/S0921-8009\(02\)00261-6](https://doi.org/10.1016/S0921-8009(02)00261-6)
- Carof, M., de Tourdonnet, S., Saulas, P., Le Floch, D., & Roger-Estrade, J. (2007). Undersowing wheat with different living mulches in a no-till system. II. Competition for light and nitrogen. *Agronomy for Sustainable Development*, 27(4), 357–365. <https://doi.org/10.1051/agro:2007017>
- Carvalho, F. P. (2006). Agriculture, pesticides, food security and food safety. *Environmental Science & Policy*, 9(7), 685–692. <https://doi.org/10.1016/j.envsci.2006.08.002>
- Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences*, 96(11), 5952–5959. <https://doi.org/10.1073/pnas.96.11.5952>
- Chaouch, S., Djelfaoui, Z., Kebaili, S., & Sandoval-Solis, S. (2021). The IDEA Method for Assessing Irrigated Cereal Farms Sustainability in Algerian Arid Zones: Case of Ouargla Region (Oued M'ya). *Sustainable Agriculture Research*, 10(3), 12.

- Charles, R., Jolliet, O., Gaillard, G., & Pellet, D. (2006). Environmental analysis of intensity level in wheat crop production using life cycle assessment. *Agriculture, Ecosystems & Environment*, 113(1–4), 216–225. <https://doi.org/10.1016/j.agee.2005.09.014>
- Chatelin, M.-H., Aubry, C., & Garcia, F. (2007). A novel method for the sustainable management of wheat crops: Exploration by simulation. *Agronomy for Sustainable Development*, 27(4), 337–345. <https://doi.org/10.1051/agro:2007014>
- Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Applied Energy*, 143, 395–413. <https://doi.org/10.1016/j.apenergy.2015.01.023>
- Chel, A., & Kaushik, G. (2011). Renewable energy for sustainable agriculture. *Agronomy for Sustainable Development*, 31(1), 91–118. <https://doi.org/10.1051/agro/2010029>
- Cheli, F., Pinotti, L., Rossi, L., & Dell’Orto, V. (2013). Effect of milling procedures on mycotoxin distribution in wheat fractions: A review. *LWT - Food Science and Technology*, 54(2), 307–314. <https://doi.org/10.1016/j.lwt.2013.05.040>
- Chianu, Jonas. N., Nkonya, E. M., Mairura, F. S., Chianu, Justina. N., & Akinnifesi, F. K. (2011). Biological nitrogen fixation and socioeconomic factors for legume production in sub-Saharan Africa: A review. *Agronomy for Sustainable Development*, 31(1), 139–154. <https://doi.org/10.1051/agro/2010004>
- Chopin, P., Mubaya, C. P., Descheemaeker, K., Öborn, I., & Bergkvist, G. (2021). Avenues for improving farming sustainability assessment with upgraded tools, sustainability framing and indicators. A review. *Agronomy for Sustainable Development*, 41(2), 19. <https://doi.org/10.1007/s13593-021-00674-3>
- Clark, M., & Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, 12(6), 064016. <https://doi.org/10.1088/1748-9326/aa6cd5>
- Clark, W. C., & Harley, A. G. (2019). Sustainability Science: Towards a Synthesis. *John F. Kennedy School of Government, Harvard University, Cambridge, MA*.
- Colantonio, A. (2009). Social sustainability: A review and critique of traditional versus emerging themes and assessment methods (M. Horner, A. Price, J. Bebbington, & R. Emmanuel, Eds.; pp. 865–885). Loughborough University. <http://www.sue-mot.org/conference/>
- Connor, M., Cuong, O. Q., Demont, M., Sander, B. O., & Nelson, K. (2022). The influence of climate change knowledge on consumer valuation of sustainably produced rice in Vietnam. *Sustainable Production and Consumption*, 31, 1–12. <https://doi.org/10.1016/j.spc.2022.01.034>
- Connor, M., de Guia, A. H., Pustika, A. B., Sudarmaji, Kobarsih, M., & Hellin, J. (2021). Rice Farming in Central Java, Indonesia—Adoption of Sustainable Farming Practices, Impacts

- and Implications. *Agronomy*, 11(5), Article 5.
<https://doi.org/10.3390/agronomy11050881>
- Cooper, M., Woodruff, D. R., Phillips, I. G., Basford, K. E., & Gilmour, A. R. (2001). Genotype-by-management interactions for grain yield and grain protein concentration of wheat. *Field Crops Research*, 69(1), 47–67. [https://doi.org/10.1016/S0378-4290\(00\)00131-3](https://doi.org/10.1016/S0378-4290(00)00131-3)
- Coradi, P. C., de Oliveira, M. B., de Oliveira Carneiro, L., Coelho de Souza, G. A., Elias, M. C., Brackmann, A., & Teodoro, P. E. (2020). Technological and sustainable strategies for reducing losses and maintaining the quality of soybean grains in real production scale storage units. *Journal of Stored Products Research*, 87, 101624.
<https://doi.org/10.1016/j.jspr.2020.101624>
- Corassa, G.M., Hansel, F.D., Lollato, R., Pires, J.L., Schwalbert, R., Amado, T.J., Guarienti, E.M., Gaviraghi, R., Bisognin, M.B., Reimche, G.B. and Santi, A.L., 2018. Nitrogen management strategies to improve yield and dough properties in hard red spring wheat. *Agronomy Journal*, 110(6), pp.2417-2429.
- Costanza, R., & Patten, B. C. (1995). Defining and predicting sustainability. *Ecological Economics*, 15(3), 193–196. [https://doi.org/10.1016/0921-8009\(95\)00048-8](https://doi.org/10.1016/0921-8009(95)00048-8)
- Coteur, I., Wustenberghs, H., Debruyne, L., Lauwers, L., & Marchand, F. (2020). How do current sustainability assessment tools support farmers’ strategic decision making? *Ecological Indicators*, 114, 106298. <https://doi.org/10.1016/j.ecolind.2020.106298>
- Couëdel, A., Edreira, J.I.R., Lollato, R.P., Archontoulis, S., Sadras, V. and Grassini, P., 2021. Assessing environment types for maize, soybean, and wheat in the United States as determined by spatio-temporal variation in drought and heat stress. *Agricultural and forest meteorology*, 307, p.108513.
- Cruppe, G., DeWolf, E., Jaenisch, B. R., Andersen Onofre, K., Valent, B., Fritz, A. K., & Lollato, R. P. (2021). Experimental and producer-reported data quantify the value of foliar fungicide to winter wheat and its dependency on genotype and environment in the U.S. central Great Plains. *Field Crops Research*, 273, 108300.
<https://doi.org/10.1016/j.fcr.2021.108300>
- Cruppe, G., Edwards, J.T. and Lollato, R.P., 2017. In-season canopy reflectance can aid fungicide and late-season nitrogen decisions on winter wheat. *Agronomy Journal*, 109(5), pp.2072-2086.
- da Silva, V. P., van der Werf, H. M. G., Spies, A., & Soares, S. R. (2010). Variability in environmental impacts of Brazilian soybean according to crop production and transport scenarios. *Journal of Environmental Management*, 91(9), 1831–1839.
<https://doi.org/10.1016/j.jenvman.2010.04.001>
- Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., & Pengue, W. A. (2008). LCA of soybean meal. *The International Journal of Life Cycle Assessment*, 13(3), 240–254. <https://doi.org/10.1065/lca2007.06.342>

- Daniel, T. C., Sharpley, A. N., & Lemunyon, J. L. (1998). Agricultural phosphorus and eutrophication: A symposium overview. *Journal of Environmental Quality*, 27(2), 251.
- Das, S; Ray, M.K., and Misha, P.K. 2023. Role of biotechnology in creating sustainable agriculture. *PLOS Sustain Transform* 2(7):e0000069
- de Olde, E. M., Bokkers, E. A. M., & de Boer, I. J. M. (2017). The Choice of the Sustainability Assessment Tool Matters: Differences in Thematic Scope and Assessment Results. *Ecological Economics*, 136, 77–85. <https://doi.org/10.1016/j.ecolecon.2017.02.015>
- de Olde, E. M., Oudshoorn, F. W., Bokkers, E. A. M., Stubsgaard, A., Sørensen, C. A. G., & De Boer, I. J. M. (2016). Assessing the Sustainability Performance of Organic Farms in Denmark. *Sustainability*, 8(9), Article 9. <https://doi.org/10.3390/su8090957>
- de Olde, E. M., Oudshoorn, F. W., Sørensen, C. A. G., Bokkers, E. A. M., & de Boer, I. J. M. (2016). Assessing sustainability at farm-level: Lessons learned from a comparison of tools in practice. *Ecological Indicators*, 66, 391–404. <https://doi.org/10.1016/j.ecolind.2016.01.047>
- Dencic, S., Kobiljski, B., Mladenov, N., Hristov, N., & Pavlovic, M. (2007). Long-Term Breeding for Bread Making Quality in Wheat. In H. T. Buck, J. E. Nisi, & N. Salomón (Eds.), *Wheat Production in Stressed Environments* (pp. 495–501). Springer Netherlands. https://doi.org/10.1007/1-4020-5497-1_60
- Deng, L., Zhang, H., Wang, C., Ma, W., Zhu, A., Zhang, F., & Jiao, X. (2021). Improving the sustainability of the wheat supply chain through multi-stakeholder engagement. *Journal of Cleaner Production*, 321, 128837. <https://doi.org/10.1016/j.jclepro.2021.128837>
- Department of Agricultural Economics Extension Publication. KFMA Research Article. KSU-AgEcon-TG-2016.1 <https://www.agmanager.info/kfma/research-articles/precision-agriculture-technology-adoption-and-obsolescence> (Retrieved July 14 2023).
- Devkota, K. P., Pasuquin, E., Elmido-Mabilangan, A., Dikitanan, R., Singleton, G. R., Stuart, A. M., Vithoonjit, D., Vidiyangkura, L., Pustika, A. B., Afriani, R., Listyowati, C. L., Keerthisena, R. S. K., Kieu, N. T., Malabayabas, A. J., Hu, R., Pan, J., & Beebout, S. E. J. (2019). Economic and environmental indicators of sustainable rice cultivation: A comparison across intensive irrigated rice cropping systems in six Asian countries. *Ecological Indicators*, 105, 199–214. <https://doi.org/10.1016/j.ecolind.2019.05.029>
- Devkota, K. P., Sudhir-Yadav, Khanda, C. M., Beebout, S. J., Mohapatra, B. K., Singleton, G. R., & Puskur, R. (2020). Assessing alternative crop establishment methods with a sustainability lens in rice production systems of Eastern India. *Journal of Cleaner Production*, 244, 118835. <https://doi.org/10.1016/j.jclepro.2019.118835>
- Diamond, D.M., Alabdulgader, A.A., de Lorgeril, M., Harcombe, Z., Kendrick, M., Malhotra, A., O'Neill, B., Ravnskov, U., Sultan, S. and Volek, J.S., 2021. Dietary recommendations for familial hypercholesterolaemia: an evidence-free zone. *BMJ evidence-based medicine*, 26(6), pp.295-301.

- Diamond, D.M., O'Neill, B.J. and Volek, J.S., 2020. Low carbohydrate diet: are concerns with saturated fat, lipids, and cardiovascular disease risk justified?. *Current Opinion in Endocrinology, Diabetes and Obesity*, 27(5), pp.291-300.
- Dincer, I., & Bicer, Y. (2018). 1.27 Life Cycle Assessment of Energy. In *Comprehensive Energy Systems* (pp. 1042–1084). Elsevier. <https://doi.org/10.1016/B978-0-12-809597-3.00134-6>
- Dong, Y., & Hauschild, M. Z. (2017). Indicators for Environmental Sustainability. *Procedia CIRP*, 61, 697–702. <https://doi.org/10.1016/j.procir.2016.11.173>
- Dubock, A. (2017). An overview of agriculture, nutrition and fortification, supplementation and biofortification: Golden Rice as an example for enhancing micronutrient intake. *Agriculture & Food Security*, 6(1), 59. <https://doi.org/10.1186/s40066-017-0135-3>
- Dyer, J. A., & Desjardins, R. L. (2003). The Impact of Farm Machinery Management on the Greenhouse Gas Emissions from Canadian Agriculture. *Journal of Sustainable Agriculture*, 22(3), 59–74. https://doi.org/10.1300/J064v22n03_07
- Eakin, H., Connors, J. P., Wharton, C., Bertmann, F., Xiong, A., & Stoltzfus, J. (2017). Identifying attributes of food system sustainability: *Emerging themes and consensus. Agriculture and Human Values*, 34(3), 757–773. <https://doi.org/10.1007/s10460-016-9754-8>
- Eichner, M. J. (1990). Nitrous Oxide Emissions from Fertilized Soils: Summary of Available Data. *Journal of Environmental Quality*, 19(2), 272–280. <https://doi.org/10.2134/jeq1990.00472425001900020013x>
- Eizenberg, E., & Jabareen, Y. (2017). Social Sustainability: A New Conceptual Framework. *Sustainability*, 9(1), Article 1. <https://doi.org/10.3390/su9010068>
- EPA. (2023). *Emission Factors for Greenhouse Gas Inventories*. Environmental Protection Agency.
- Espinoza-Orias, N., Stichnothe, H., & Azapagic, A. (2011). The carbon footprint of bread. *The International Journal of Life Cycle Assessment*, 16(4), 351–365. <https://doi.org/10.1007/s11367-011-0271-0>
- Evans, L. T., & Fischer, R. A. (1999). Yield Potential: Its Definition, Measurement, and Significance. *Crop Science*, 39(6), 1544–1551. <https://doi.org/10.2135/cropsci1999.3961544x>
- Ewert, F., Baatz, R. and Finger, R., 2023. Agroecology for a Sustainable Agriculture and Food System: From Local Solutions to Large-Scale Adoption. *Annual Review of Resource Economics*, 15.
- Fabiani, S., Vanino, S., Napoli, R., & Nino, P. (2020). Water energy food nexus approach for sustainability assessment at farm level: An experience from an intensive agricultural area

- in central Italy. *Environmental Science & Policy*, 104, 1–12.
<https://doi.org/10.1016/j.envsci.2019.10.008>
- Fabiani, S., Vanino, S., Napoli, R., Zajíček, A., Duffková, R., Evangelou, E., & Nino, P. (2020). Assessment of the economic and environmental sustainability of Variable Rate Technology (VRT) application in different wheat intensive European agricultural areas. A Water energy food nexus approach. *Environmental Science & Policy*, 114, 366–376.
<https://doi.org/10.1016/j.envsci.2020.08.019>
- Fadul-Pacheco, L., Wattiaux, M. A., Espinoza-Ortega, A., Sánchez-Vera, E., & Arriaga-Jordán, C. M. (2013). Evaluation of Sustainability of Smallholder Dairy Production Systems in the Highlands of Mexico During the Rainy Season. *Agroecology and Sustainable Food Systems*, 37(8), 882–901. <https://doi.org/10.1080/21683565.2013.775990>
- Fageria, N. K., & Baligar, V. C. (2005). Enhancing Nitrogen Use Efficiency in Crop Plants. In *Advances in Agronomy* (Vol. 88, pp. 97–185). Academic Press.
[https://doi.org/10.1016/S0065-2113\(05\)88004-6](https://doi.org/10.1016/S0065-2113(05)88004-6)
- Fageria, N. K., Slaton, N. A., & Baligar, V. C. (2003). Nutrient Management for Improving Lowland Rice Productivity and Sustainability. In *Advances in Agronomy* (Vol. 80, pp. 63–152). Academic Press. [https://doi.org/10.1016/S0065-2113\(03\)80003-2](https://doi.org/10.1016/S0065-2113(03)80003-2)
- Fahad, S., Saud, S., Akhter, A., Bajwa, A. A., Hassan, S., Battaglia, M., Adnan, M., Wahid, F., Datta, R., Babur, E., Danish, S., Zarei, T., & Irshad, I. (2021). Bio-based integrated pest management in rice: An agro-ecosystems friendly approach for agricultural sustainability. *Journal of the Saudi Society of Agricultural Sciences*, 20(2), 94–102.
<https://doi.org/10.1016/j.jssas.2020.12.004>
- Fallahpour, F., Aminghafouri, A., Ghalegolab Behbahani, A., & Bannayan, M. (2012). The environmental impact assessment of wheat and barley production by using life cycle assessment (LCA) methodology. *Environment, Development and Sustainability*, 14(6), 979–992. <https://doi.org/10.1007/s10668-012-9367-3>
- FAO (Ed.). (2014). SAFA guidelines: Sustainability assessment of food and agriculture systems (Version 3.0). Food and Agriculture Organization of the United Nations.
<http://www.fao.org/nr/sustainability/sustainability-assessments-safa>
- FAO, (Food and Agriculture Organization). (1989). Sustainable Development and Natural Resources Management. <https://doi.org/10.1016/j.jclepro.2006.12.006>
- FAO, (Food and Agriculture Organization). (2014). The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture.
<https://www.fao.org/3/bl496e/bl496e.pdf>
- FAO. (2020). Food Balances (2010-). License: CC BY-NC-SA 3.0 IGO. Extracted from:
<https://www.fao.org/faostat/en/#data/FBS>. Data of Access: 09-06-2023.

- FAO. (2021). Crops and livestock products. License: CC BY-NC-SA 3.0 IGO. Extracted from: <https://www.fao.org/faostat/en/#data/QCL>. Data of Access: 10-03-2023.
- Feng, H., Zhao, J., Hollberg, A., & Habert, G. (2023). Where to focus? Developing a LCA impact category selection tool for manufacturers of building materials. *Journal of Cleaner Production*, 405, 136936. <https://doi.org/10.1016/j.jclepro.2023.136936>
- Feng, M., Chen, Y., Duan, W., Fang, G., Li, Z., Jiao, L., Sun, F., Li, Y., & Hou, Y. (2022). Comprehensive evaluation of the water-energy-food nexus in the agricultural management of the Tarim River Basin, Northwest China. *Agricultural Water Management*, 271, 107811. <https://doi.org/10.1016/j.agwat.2022.107811>
- Field to Market. (2022). Fieldprint Platform. Field to Market. <https://fieldtomarket.org/our-programs/fieldprint-platform/>
- Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91(1), 1–21. <https://doi.org/10.1016/j.jenvman.2009.06.018>
- Fischer, R. A. (2015). Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Research*, 182, 9–18. <https://doi.org/10.1016/j.fcr.2014.12.006>
- Fischer, T., Ammar, K., Monasterio, I. O., Monjardino, M., Singh, R., & Verhulst, N. (2022). Sixty years of irrigated wheat yield increase in the Yaqui Valley of Mexico: Past drivers, prospects and sustainability. *Field Crops Research*, 283, 108528. <https://doi.org/10.1016/j.fcr.2022.108528>
- Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K. and Helkowski, J.H. (2005). Global consequences of land use. *Science*, 309(5734), 570–574.
- Franke, A. C., van den Brand, G. J., Vanlauwe, B., & Giller, K. E. (2018). Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agriculture, Ecosystems & Environment*, 261, 172–185. <https://doi.org/10.1016/j.agee.2017.09.029>
- Freney, J. R. (1997). Emission of nitrous oxide from soils used for agriculture. *Nutrient Cycling in Agroecosystems*, 49(1), 1–6. <https://doi.org/10.1023/A:1009702832489>
- Gadanakis, Y., Bennett, R., Park, J., & Areal, F. J. (2015). Evaluating the Sustainable Intensification of arable farms. *Journal of Environmental Management*, 150, 288–298. <https://doi.org/10.1016/j.jenvman.2014.10.005>
- Gaju, O., Allard, V., Martre, P., Snape, J. W., Heumez, E., LeGouis, J., Moreau, D., Bogard, M., Griffiths, S., Orford, S., Hubbart, S., & Foulkes, M. J. (2011). Identification of traits to improve the nitrogen-use efficiency of wheat genotypes. *Field Crops Research*, 123(2), 139–152. <https://doi.org/10.1016/j.fcr.2011.05.010>

- Gan, Y., Liang, C., Chai, Q., Lemke, R.L., Campbell, C.A. and Zentner, R.P., (2014). Improving farming practices reduces the carbon footprint of spring wheat production. *Nature Communications*, 5(1), p.5012.
- Gan, Y., Liang, C., Hamel, C., Cutforth, H., & Wang, H. (2011). Strategies for reducing the carbon footprint of field crops for semiarid areas: A review. *Agronomy for Sustainable Development*, 31, 643-656.
- Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy*, 36, S23–S32.
<https://doi.org/10.1016/j.foodpol.2010.10.010>
- Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J., & Godfray, H. C. J. (2013). Sustainable Intensification in Agriculture: Premises and Policies. *Science*, 341(6141), 33–34.
<https://doi.org/10.1126/science.1234485>
- Gathorne-Hardy, A. (2013). A Life Cycle Assessment (LCA) of Greenhouse Gas Emissions from SRI and Flooded Rice Production in SE India. *Taiwan Water Conservancy Journal*.
<https://doi.org/10.35648/20.500.12413/11781/ii250>
- Gautam, P., Lal, B., Panda, B. B., Bihari, P., Chatterjee, D., Singh, T., Nayak, P. K., & Nayak, A. K. (2021). Alteration in agronomic practices to utilize rice fallows for higher system productivity and sustainability. *Field Crops Research*, 260, 108005.
<https://doi.org/10.1016/j.fcr.2020.108005>
- Gayatri, S., Gasso-tortajada, V., & Vaarst, M. (2016). Assessing Sustainability of Smallholder Beef Cattle Farming in Indonesia: A Case Study Using the FAO SAFA Framework. *Journal of Sustainable Development*, 9(3), 236. <https://doi.org/10.5539/jsd.v9n3p236>
- Gerrard, C. L., Smith, L. G., Pearce, B., Padel, S., Hitchings, R., Measures, M., & Cooper, N. (2012). Public Goods and Farming. In E. Lichtfouse (Ed.), *Farming for Food and Water Security* (pp. 1–22). *Springer Netherlands*. https://doi.org/10.1007/978-94-007-4500-1_1
- Geus, Y. N., Goggi, A. S., & Pollak, L. M. (2008). Seed quality of high protein corn lines in low input and conventional farming systems. *Agronomy for Sustainable Development*, 28(4), 541–550. <https://doi.org/10.1051/agro:2008023>
- Ghasemi-Mobtaker, H., Kaab, A., & Rafiee, S. (2020). Application of life cycle analysis to assess environmental sustainability of wheat cultivation in the west of Iran. *Energy*, 193, 116768. <https://doi.org/10.1016/j.energy.2019.116768>
- Ghimire, R., Machado, S., & Rhinhart, K. (2015). Long-Term Crop Residue and Nitrogen Management Effects on Soil Profile Carbon and Nitrogen in Wheat–Fallow Systems. *Agronomy Journal*, 107(6), 2230–2240. <https://doi.org/10.2134/agronj14.0601>

- Giacomeli, R., Carlesso, R., Petry, M. T., Chechi, L., Beutler, A. N., Fulaneti, F. S., & Ferrazza, C. M. (2021). Improving irrigation, crop, and soil management for sustainable soybean production in Southern Brazilian lowlands. *Scientia Agricola*, 79. <https://doi.org/10.1590/1678-992X-2021-0115>
- Giordano, N., Sadras, V.O. and Lollato, R.P., 2023. Late-season nitrogen application increases grain protein concentration and is neutral for yield in wheat. A global meta-analysis. *Field Crops Research*, 290, p.108740.
- Giuliana, V., Lucia, M., Marco, R., & Simone, V. (2022). Environmental life cycle assessment of rice production in northern Italy: A case study from Vercelli. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-022-02109-x>
- Giusti, G., Almeida, G., Apresentação, M., Galvão, L., Knudsen, M., Djomo, S., & Silva, D. (2022). Environmental impacts management of grain and sweet maize through life cycle assessment in São Paulo, Brazil. *International Journal of Environmental Science and Technology*, 20. <https://doi.org/10.1007/s13762-022-04418-y>
- Glaser, J. A., & Matten, S. R. (2003). Sustainability of insect resistance management strategies for transgenic Bt corn. *Biotechnology Advances*, 22(1), 45–69. <https://doi.org/10.1016/j.biotechadv.2003.08.016>
- Glavič, P., & Lukman, R. (2007). Review of sustainability terms and their definitions. *Journal of Cleaner Production*, 15(18), 1875–1885. <https://doi.org/10.1016/j.jclepro.2006.12.006>
- Goglio, P., Smith, W. N., Grant, B. B., Desjardins, R. L., McConkey, B. G., Campbell, C. A., & Nemecek, T. (2015). Accounting for soil carbon changes in agricultural life cycle assessment (LCA): A review. *Journal of Cleaner Production*, 104, 23–39. <https://doi.org/10.1016/j.jclepro.2015.05.040>
- Gómez-Limón, J. A., & Sanchez-Fernandez, G. (2010). Empirical evaluation of agricultural sustainability using composite indicators. *Ecological Economics*, 69(5), 1062–1075. <https://doi.org/10.1016/j.ecolecon.2009.11.027>
- Goodland, R. (1995). The Concept of Environmental Sustainability. *Annual Review of Ecology and Systematics*, 26(1), 1–24. <https://doi.org/10.1146/annurev.es.26.110195.000245>
- Goucher, L., Bruce, R., Cameron, D. D., Lenny Koh, S. C., & Horton, P. (2017). The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. *Nature Plants*, 3(3), 17012. <https://doi.org/10.1038/nplants.2017.12>
- Graham, R. D. (2008). Micronutrient Deficiencies in Crops and Their Global Significance. In B. J. Alloway (Ed.), *Micronutrient Deficiencies in Global Crop Production* (pp. 41–61). *Springer Netherlands*. https://doi.org/10.1007/978-1-4020-6860-7_2
- Grassini, P., & Cassman, K. G. (2012). High-yield maize with large net energy yield and small global warming intensity. *Proceedings of the National Academy of Sciences*, 109(4), 1074–1079. <https://doi.org/10.1073/pnas.1116364109>

- Grassini, P., Eskridge, K.M. and Cassman, K.G., 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature communications*, 4(1), p.2918.
- Greer, K., Martins, C., White, M., & Pittelkow, C. M. (2020). Assessment of high-input soybean management in the US Midwest: Balancing crop production with environmental performance. *Agriculture, Ecosystems & Environment*, 292, 106811. <https://doi.org/10.1016/j.agee.2019.106811>
- Griffin TW, Lowenberg-DeBoer J, Lambert DM, Peone J, Payne T and Daberkow SG. 2004. Adoption, Profitability, and Making Better Use of Precision Farming Data. Staff Paper #04-06 Department of Agricultural Economics, Purdue University, USA. <http://ageconsearch.umn.edu/bitstream/28615/1/sp04-06.pdf> (Retrieved July 14, 2023).
- Griffin TW, Miller NJ, Torrez C, Ciampitti I and Sharda A 2016. Precision Agriculture Technology Adoption and Obsolescence. Kansas State University
- Guo, X., Wu, H., Chen, D., Ye, Z., Shen, Y., Liu, J., & Cheng, S. (2020). Estimation and prediction of pollutant emissions from agricultural and construction diesel machinery in the Beijing-Tianjin-Hebei (BTH) region, China☆. *Environmental Pollution*, 260, 113973. <https://doi.org/10.1016/j.envpol.2020.113973>
- Gustafson, D., Gutman, A., Leet, W., Drewnowski, A., Fanzo, J., & Ingram, J. (2016). Seven Food System Metrics of Sustainable Nutrition Security. *Sustainability*, 8(3), Article 3. <https://doi.org/10.3390/su8030196>
- Habibi, E., Niknejad, Y., Fallah, H., Dastan, S., & Tari, D. B. (2019). Life cycle assessment of rice production systems in different paddy field size levels in north of Iran. *Environmental Monitoring and Assessment*, 191(4), 202. <https://doi.org/10.1007/s10661-019-7344-0>
- Hani, F., Braga, F., Stampfli, A., Keller, T., Fischer, M., & Porsche, H. (2003). RISE, a Tool for Holistic Sustainability Assessment at the Farm Level. *International Food and Agribusiness Management Review*, 06.
- Hansen, J. W., & Jones, J. W. (1996). A systems framework for characterizing farm sustainability. *Agricultural Systems*, 51(2), 185–201. [https://doi.org/10.1016/0308-521X\(95\)00036-5](https://doi.org/10.1016/0308-521X(95)00036-5)
- Hardi, P., & Zdan, T. (1997). *Assessing Sustainable Development: Principles in Practice*. The International Institute for Sustainable Development.
- Harun, S. N., Hanafiah, M. M., & Noor, N. M. (2022). Rice Straw Utilisation for Bioenergy Production: A Brief Overview. *Energies*, 15(15), Article 15. <https://doi.org/10.3390/en15155542>
- Hatim, M., Majidian, M., Tahmasebi, M., & Nabavi-Pelesaraei, A. (2023). Life cycle assessment, life cycle cost, and exergoeconomic analysis of different tillage systems in

- safflower production by micronutrients. *Soil and Tillage Research*, 233, 105795. <https://doi.org/10.1016/j.still.2023.105795>
- Hawkesford, M.J. and Griffiths, S., 2019. Exploiting genetic variation in nitrogen use efficiency for cereal crop improvement. *Current opinion in plant biology*, 49, pp.35-42. Bajgain, R., Xiao, X., Basara, J., Wagle, P., Zhou, Y., Mahan, H., Gowda, P., McCarthy, H.R., Northup, B., Neel, J. and Steiner, J. (2018). Carbon dioxide and water vapor fluxes in winter wheat and tallgrass prairie in central Oklahoma. *Science of the Total Environment*, 644, pp.1511-1524.
- He, H., Liu, L., Munir, S., Bashir, N. H., Wang, Y., Yang, J., & Li, C. (2019). Crop diversity and pest management in sustainable agriculture. *Journal of Integrative Agriculture*, 18(9), 1945–1952. [https://doi.org/10.1016/S2095-3119\(19\)62689-4](https://doi.org/10.1016/S2095-3119(19)62689-4)
- He, X., Qiao, Y., Liang, L., Knudsen, M. T., & Martin, F. (2018). Environmental life cycle assessment of long-term organic rice production in subtropical China. *Journal of Cleaner Production*, 176, 880–888. <https://doi.org/10.1016/j.jclepro.2017.12.045>
- Hegewald, H., Wensch-Dorendorf, M., Sieling, K. and Christen, O., 2018. Impacts of break crops and crop rotations on oilseed rape productivity: A review. *European journal of agronomy*, 101, pp.63-77.
- Heller, M. C., & Keoleian, G. A. (2003). Assessing the sustainability of the US food system: A life cycle perspective. *Agricultural Systems*, 76(3), 1007–1041. [https://doi.org/10.1016/S0308-521X\(02\)00027-6](https://doi.org/10.1016/S0308-521X(02)00027-6)
- Henderson, R., Gastelle, J., & Caffarelli, P. (2023). *Transportation of U.S. Grains: A Modal Share Analysis, August 2023*. U.S. Department of Agriculture, Agricultural Marketing Service. <https://doi.org/10.9752/TS049.08-2023>
- Herforth, A., Frongillo, E. A., Sassi, F., Mclean, M. S., Arabi, M., Tirado, C., Remans, R., Mantilla, G., Thomson, M., & Pingali, P. (2014). Toward an integrated approach to nutritional quality, environmental sustainability, and economic viability: Research and measurement gaps. *Annals of the New York Academy of Sciences*, 1332(1), 1–21. <https://doi.org/10.1111/nyas.12552>
- Hill, J., Goodkind, A., Tessum, C., Thakrar, S., Tilman, D., Polasky, S., Smith, T., Hunt, N., Mullins, K., Clark, M., & Marshall, J. (2019). Air-quality-related health damages of maize. *Nature Sustainability*, 2(5), 397–403. <https://doi.org/10.1038/s41893-019-0261-y>
- Hodgson, E. W., McMaizeack, B. P., Tilmon, K., & Knodel, J. J. (2012). Management Recommendations for Soybean Aphid (Hemiptera: Aphididae) in the United States. *Journal of Integrated Pest Management*, 3(1), E1–E10. <https://doi.org/10.1603/IPM11019>
- Holka, M. (2016). Life Cycle Assessment (LCA) of Winter Wheat in an Intensive Crop Production System in Wielkopolska Region (Poland). *Applied Ecology and Environmental Research*, 14(3), 535–545. https://doi.org/10.15666/aeer/1403_535545

- Hong-xing, X., Ya-jun, Y., Yan-hui, L., Xu-song, Z., Jun-ce, T., Feng-xiang, L., Qiang, F., & Zhong-xian, L. (2017). Sustainable Management of Rice Insect Pests by Non-Chemical-Insecticide Technologies in China. *Rice Science*, 24(2), 61–72. <https://doi.org/10.1016/j.rsci.2017.01.001>
- Houshyar, E., & Grundmann, P. (2017). Environmental impacts of energy use in wheat tillage systems: A comparative life cycle assessment (LCA) study in Iran. *Energy*, 122, 11–24. <https://doi.org/10.1016/j.energy.2017.01.069>
- Huang, L., Wu, J., & Yan, L. (2015). Defining and measuring urban sustainability: A review of indicators. *Landscape Ecology*, 30(7), 1175–1193. <https://doi.org/10.1007/s10980-015-0208-2>
- Huang, S., Zhang, W., Yu, X., & Huang, Q. (2010). Effects of long-term fertilization on corn productivity and its sustainability in an Ultisol of southern China. *Agriculture, Ecosystems & Environment*, 138(1), 44–50. <https://doi.org/10.1016/j.agee.2010.03.015>
- Hunt, J. R., Kirkegaard, J. A., Harris, F. A., Porker, K. D., Rattey, A. R., Collins, M. J., Celestina, C., Cann, D. J., Hochman, Z., Lilley, J. M., & Flohr, B. M. (2021). Exploiting genotype × management interactions to increase rainfed crop production: A case study from south-eastern Australia. *Journal of Experimental Botany*, 72(14), 5189–5207. <https://doi.org/10.1093/jxb/erab250>
- Hutchins, M. J., & Sutherland, J. W. (2008). An exploration of measures of social sustainability and their application to supply chain decisions. *Journal of Cleaner Production*, 16(15), 1688–1698. <https://doi.org/10.1016/j.jclepro.2008.06.001>
- Ibendahl, G., O'Brien, D., Holman, J., Lancaster, S., & Haag, L. (2021). *2021 Farm Management Guides for Non-Irrigated Crops*. Agmanager - Kansas State University. <https://www.agmanager.info/farm-budgets/2021-farm-management-guides-non-irrigated-crops>
- Ibendahl, G., O'Brien, D., Holman, J., Lancaster, S., & Haag, L. (2022). *2022 Farm Management Guides for Non-Irrigated Crops*. Agmanager - Kansas State University. <https://www.agmanager.info/farm-budgets/2022-farm-management-guides-non-irrigated-crops>
- Imran, Amanullah, & M. Al-Tawaha, A. R. (2021). Carbon Sources Application Increase Wheat Yield and Soil Fertility. *Communications in Soil Science and Plant Analysis*, 52(7), 695–703. <https://doi.org/10.1080/00103624.2020.1865397>
- Ingrao, C., Matarazzo, A., Gorjian, S., Adamczyk, J., Failla, S., Primerano, P., & Huisinigh, D. (2021). Wheat-straw derived bioethanol production: A review of Life Cycle Assessments. *Science of The Total Environment*, 781, 146751. <https://doi.org/10.1016/j.scitotenv.2021.146751>

- IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.
- Ishfaq, M., Akbar, N., Zulfiqar, U., Ali, N., Ahmad, M., Anjum, S. A., & Farooq, M. (2021). Influence of water management techniques on milling recovery, grain quality and mercury uptake in different rice production systems. *Agricultural Water Management*, 243, 106500. <https://doi.org/10.1016/j.agwat.2020.106500>
- ISO. (2006). *Environmental management—Life cycle assessment—Principles and framework* (14040). ISO. <https://www.iso.org/standard/37456.html>
- Jabareen, Y. (2008). A New Conceptual Framework for Sustainable Development. *Environment, Development and Sustainability*, 10(2), 179–192. <https://doi.org/10.1007/s10668-006-9058-z>
- Jaenisch, B. R., Munaro, L. B., Bastos, L. M., Moraes, M., Lin, X., & Lollato, R. P. (2021). On-farm data-rich analysis explains yield and quantifies yield gaps of winter wheat in the U.S. central Great Plains. *Field Crops Research*, 272, 108287. <https://doi.org/10.1016/j.fcr.2021.108287>
- Jaenisch, B.R., de Oliveira Silva, A., DeWolf, E., Ruiz-Diaz, D.A. and Lollato, R.P., 2019. Plant population and fungicide economically reduced winter wheat yield gap in Kansas. *Agronomy Journal*, 111(2), pp.650-665.
- Janker, J., & Mann, S. (2018). Understanding the social dimension of sustainability in agriculture: A critical review of sustainability assessment tools. *Environment, Development and Sustainability*, 22(3), 1671–1691. <https://doi.org/10.1007/s10668-018-0282-0>
- Jia, F., Peng, S., Green, J., Koh, L., & Chen, X. (2020). Soybean supply chain management and sustainability: A systematic literature review. *Journal of Cleaner Production*, 255, 120254. <https://doi.org/10.1016/j.jclepro.2020.120254>
- Jimmy, A. N., Khan, N. A., Hossain, M. N., & Sujauddin, M. (2017). Evaluation of the environmental impacts of rice paddy production using life cycle assessment: Case study in Bangladesh. *Modeling Earth Systems and Environment*, 3(4), 1691–1705. <https://doi.org/10.1007/s40808-017-0368-y>
- Jirapornvaree, I., Suppadit, T., & Kumar, V. (2021). Assessing the economic and environmental impact of jasmine rice production: Life cycle assessment and Life Cycle Costs analysis. *Journal of Cleaner Production*, 303, 127079. <https://doi.org/10.1016/j.jclepro.2021.127079>
- Johnson, J. M.-F., Franzluebbers, A. J., Weyers, S. L., & Reicosky, D. C. (2007). Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution*, 150(1), 107–124. <https://doi.org/10.1016/j.envpol.2007.06.030>

- Jones-Garcia, E., & Krishna, V. V. (2021). Farmer adoption of sustainable intensification technologies in the maize systems of the Global South. A review. *Agronomy for Sustainable Development*, 41(1), 8. <https://doi.org/10.1007/s13593-020-00658-9>
- Júnior, R.D.S.N., Ewert, F., Webber, H., Martre, P., Hertel, T.W., van Ittersum, M.K. and Asseng, S., 2022. Needed global wheat stock and crop management in response to the war in Ukraine. *Global Food Security*, 35, p.100662.
- Kang, G. S., Beri, V., Sidhu, B. S., & Rupela, O. P. (2005). A new index to assess soil quality and sustainability of wheat-based cropping systems. *Biology and Fertility of Soils*, 41(6), 389–398. <https://doi.org/10.1007/s00374-005-0857-4>
- Kansas Department of Revenue. (2022). *Grain Elevator Appraisal Guide for the State of Kansas*. <https://www.ksrevenue.gov/pdf/2022KSGrainElevatorGuide.pdf>
- Karlen, D. L., Varvel, G. E., Johnson, J. M. F., Baker, J. M., Osborne, S. L., Novak, J. M., Adler, P. R., Roth, G. W., & Birrell, S. J. (2011). Monitoring Soil Quality to Assess the Sustainability of Harvesting Corn Stover. *Agronomy Journal*, 103(1), 288–295. <https://doi.org/10.2134/agronj2010.0160s>
- KDA, & LUSO. (2022). *Kansas Custom Rates 2022*. Kansas Department of Agriculture and Kansas State University Land Use Survey Office. https://www.agmanager.info/sites/default/files/pdf/2022_CustomRates_05-19-22.pdf
- Keikha, M., Darzi- Naftchali, A., Motevali, A., & Valipour, M. (2023). Effect of nitrogen management on the environmental and economic sustainability of wheat production in different climates. *Agricultural Water Management*, 276, 108060. <https://doi.org/10.1016/j.agwat.2022.108060>
- Khan, M. A. (1995). Sustainable development: The key concepts, issues and implications. Keynote paper given at the international sustainable development research conference, 27–29 march 1995, Manchester, UK. *Sustainable Development*, 3(2), 63–69. <https://doi.org/10.1002/sd.3460030203>
- Khan, M., & Latif, N. (2010). Energy requirements and economic analysis of wheat, rice and barley production in Australia. *Soil & Environment*, 21, 61–68.
- Kim, S., & Dale, B. E. (2008). Effects of Nitrogen Fertilizer Application on Greenhouse Gas Emissions and Economics of Corn Production. *Environmental Science & Technology*, 42(16), 6028–6033. <https://doi.org/10.1021/es800630d>
- Kim, S., Dale, B. E., & Jenkins, R. (2009). Life cycle assessment of corn grain and corn stover in the United States. *The International Journal of Life Cycle Assessment*, 14(2), 160–174. <https://doi.org/10.1007/s11367-008-0054-4>
- Kim, S., Dale, B. E., & Keck, P. (2014). Energy Requirements and Greenhouse Gas Emissions of Maize Production in the USA. *BioEnergy Research*, 7(2), 753–764. <https://doi.org/10.1007/s12155-013-9399-z>

- Kirkegaard, J., Christen, O., Krupinsky, J., & Layzell, D. (2008). Break crop benefits in temperate wheat production. *Field Crops Research*, 107(3), 185–195. <https://doi.org/10.1016/j.fcr.2008.02.010>
- Knudsen, M. T., Yu-Hui, Q., Yan, L., & Halberg, N. (2010). Environmental assessment of organic soybean (*Glycine max.*) imported from China to Denmark: A case study. *Journal of Cleaner Production*, 18(14), 1431–1439. <https://doi.org/10.1016/j.jclepro.2010.05.022>
- Konefal, J., de Olde, E. M., Hatanaka, M., & Oosterveer, P. J. M. (2023). Signs of agricultural sustainability: A global assessment of sustainability governance initiatives and their indicators in crop farming. *Agricultural Systems*, 208, 103658. <https://doi.org/10.1016/j.agry.2023.103658>
- Kong, A. Y. Y., Six, J., Bryant, D. C., Denison, R. F., & Van Kessel, C. (2005). The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems. *Soil Science Society of America Journal*, 69(4), 1078–1085. <https://doi.org/10.2136/sssaj2004.0215>
- Kong, L. (2014). Maize residues, soil quality, and wheat growth in China. A review. *Agronomy for Sustainable Development*, 34(2), 405–416. <https://doi.org/10.1007/s13593-013-0182-5>
- Król-Badziak, A., Pishgar-Komleh, S. H., Rozakis, S., & Księżak, J. (2021). Environmental and socio-economic performance of different tillage systems in maize grain production: Application of Life Cycle Assessment and Multi-Criteria Decision Making. *Journal of Cleaner Production*, 278, 123792. <https://doi.org/10.1016/j.jclepro.2020.123792>
- Kulak, M., Nemecek, T., Frossard, E., Chable, V., & Gaillard, G. (2015). Life cycle assessment of bread from several alternative food networks in Europe. *Journal of Cleaner Production*, 90, 104–113. <https://doi.org/10.1016/j.jclepro.2014.10.060>
- Kumar, A., Nayak, A. K., Sharma, S., Senapati, A., Mitra, D., Mohanty, B., Prabhukarthikeyan, S. R., Sabarinathan, K. G., Mani, I., Garhwal, R. S., Thankappan, S., Sagarika, M. S., de los SANTOS-VILLALOBOS, S., & Panneerselvam, P. (2022). Recycling of rice straw—a sustainable approach for ensuring environmental quality and economic security: A review. *Pedosphere*. <https://doi.org/10.1016/j.pedsph.2022.06.036>
- Kumar, R., Mishra, J. S., Rao, K. K., Mondal, S., Hazra, K. K., Choudhary, J. S., Hans, H., & Bhatt, B. P. (2020). Crop rotation and tillage management options for sustainable intensification of rice-fallow agro-ecosystem in eastern India. *Scientific Reports*, 10(1), Article 1. <https://doi.org/10.1038/s41598-020-67973-9>
- Kumar, V., Mahajan, G., Dahiya, S., & Chauhan, B. S. (2020). Challenges and opportunities for weed management in no-till farming systems. *No-till Farming Systems for Sustainable Agriculture: Challenges and Opportunities*, 107–125.
- Lairez, J., Affholder, F., Scopel, E., Leudpanhane, B., & Wery, J. (2023). Sustainability assessment of cropping systems: A field-based approach on family farms. Application to

- maize cultivation in Southeast Asia. *European Journal of Agronomy*, 143, 126716.
<https://doi.org/10.1016/j.eja.2022.126716>
- Lal, R. (2003). Global Potential of Soil Carbon Sequestration to Mitigate the Greenhouse Effect. *Critical Reviews in Plant Sciences*, 22(2), 151–184. <https://doi.org/10.1080/713610854>
- Lal, R. (2004). Carbon emission from farm operations. *Environment International*, 30(7), 981–990. <https://doi.org/10.1016/j.envint.2004.03.005>
- Langeroodi, A. reza S., Adewale Osipitan, O., & Radicetti, E. (2019). Benefits of sustainable management practices on mitigating greenhouse gas emissions in soybean crop (*Glycine max*). *Science of The Total Environment*, 660, 1593–1601.
<https://doi.org/10.1016/j.scitotenv.2019.01.074>
- Larson, W. E., Pierce, F. J., & Dowdy, R. H. (1983). The Threat of Soil Erosion to Long-Term Crop Production. *Science*, 219(4584), 458–465.
<https://doi.org/10.1126/science.219.4584.458>
- Latruffe, L., Diazabakana, A., Bockstaller, C., Desjeux, Y., Finn, J., Kelly, E., Ryan, M., & Uthes, S. (2016). Measurement of sustainability in agriculture: A review of indicators. *Studies in Agricultural Economics*, 118(3), 123–130. <https://doi.org/10.7896/j.1624>
- Lawes, R., Chen, C., Whish, J., Meier, E., Ouzman, J., Gobbett, D., Vadakattu, G., Ota, N. and van Rees, H., 2021. Applying more nitrogen is not always sufficient to address dryland wheat yield gaps in Australia. *Field Crops Research*, 262, p.108033.
- Leach, A.M., Emery, K.A., Gephart, J., Davis, K.F., Erisman, J.W., Leip, A., Pace, M.L., D’Odorico, P., Carr, J., Noll, L.C. and Castner, E., 2016. Environmental impact food labels combining carbon, nitrogen, and water footprints. *Food Policy*, 61, pp.213-223.
- Le-bail, A., Dessev, T., Jury, V., Zuniga, R., Park, T., & Pitroff, M. (2010). Energy demand for selected bread making processes: Conventional versus part baked frozen technologies. *Journal of Food Engineering*, 96(4), 510–519.
<https://doi.org/10.1016/j.jfoodeng.2009.08.039>
- Lee, K.-M., & Inaba, A. (2004). *Life Cycle Assessment Best Practices of ISO 14040 Series*. Center for Ecodesign and LCA (CEL). <http://ecodesign.ajou.ac.kr>
- Lewandowski, I., Härdtlein, M., & Kaltschmitt, M. (1999). Sustainable Crop Production: Definition and Methodological Approach for Assessing and Implementing Sustainability. *Crop Science*, 39(1), 184-193.
<https://doi.org/10.2135/cropsci1999.0011183X003900010029x>
- Li, J., Cui, J., Sui, P., Yue, S., Yang, J., Lv, Z., Wang, D., Chen, X., Sun, B., Ran, M., & Chen, Y. (2021). Valuing the synergy in the water-energy-food nexus for cropping systems: A case in the North China Plain. *Ecological Indicators*, 127, 107741.
<https://doi.org/10.1016/j.ecolind.2021.107741>

- Li, K., Yang, X., Liu, Z., Zhang, T., Lu, S., & Liu, Y. (2014). Low yield gap of winter wheat in the North China Plain. *European Journal of Agronomy*, 59, 1–12. <https://doi.org/10.1016/j.eja.2014.04.007>
- Li, S., Thompson, M., Moussavi, S., & Dvorak, B. (2021). Life cycle and economic assessment of corn production practices in the western US Corn Belt. *Sustainable Production and Consumption*, 27, 1762–1774. <https://doi.org/10.1016/j.spc.2021.04.021>
- Li, T., Gao, J., Bai, L., Wang, Y., Huang, J., Kumar, M., & Zeng, X. (2019). Influence of green manure and rice straw management on soil organic carbon, enzyme activities, and rice yield in red paddy soil. *Soil and Tillage Research*, 195, 104428. <https://doi.org/10.1016/j.still.2019.104428>
- Liang, K., Zhong, X., Huang, N., Lampayan, R. M., Liu, Y., Pan, J., Peng, B., Hu, X., & Fu, Y. (2017). Nitrogen losses and greenhouse gas emissions under different N and water management in a subtropical double-season rice cropping system. *Science of The Total Environment*, 609, 46–57. <https://doi.org/10.1016/j.scitotenv.2017.07.118>
- Linlaud, N. E., Puppo, M. C., & Ferrero, C. (2009). Effect of Hydrocolloids on Water Absorption of Wheat Flour and Farinograph and Textural Characteristics of Dough. *Cereal Chemistry*, 86(4), 376–382. <https://doi.org/10.1094/CCHEM-86-4-0376>
- Linquist, B., Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, 18(1), 194–209. <https://doi.org/10.1111/j.1365-2486.2011.02502.x>
- Liska, A. J., Yang, H. S., Bremer, V. R., Klopfenstein, T. J., Walters, D. T., Erickson, G. E., & Cassman, K. G. (2009). Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol. *Journal of Industrial Ecology*, 13(1), 58–74. <https://doi.org/10.1111/j.1530-9290.2008.00105.x>
- Littig, B., & Griessler, E. (2005). Social sustainability: A catchword between political pragmatism and social theory. *International Journal of Sustainable Development*, 8(1/2), 65. <https://doi.org/10.1504/IJSD.2005.007375>
- Liu, B.-Y., Liu, W.-S., Lin, B.-J., Liu, W.-X., Han, S.-W., Zhao, X., & Zhang, H.-L. (2022). Sustainable management practices to improve the water use efficiency of winter wheat in the North China Plain: A meta-analysis. *Agronomy for Sustainable Development*, 42(2), 33. <https://doi.org/10.1007/s13593-022-00766-8>
- Liu, L., Zheng, X., Wei, X., Kai, Z., & Xu, Y. (2021). Excessive application of chemical fertilizer and organophosphorus pesticides induced total phosphorus loss from planting causing surface water eutrophication. *Scientific Reports*, 11(1), Article 1. <https://doi.org/10.1038/s41598-021-02521-7>
- Liu, Q., Sun, X., Wu, W., Liu, Z., Fang, G., & Yang, P. (2022). Agroecosystem services: A review of concepts, indicators, assessment methods and future research perspectives. *Ecological Indicators*, 142, 109218. <https://doi.org/10.1016/j.ecolind.2022.109218>

- Liu, X., Bakshi, B. R., Rugani, B., de Souza, D. M., Bare, J., Johnston, J. M., Laurent, A., & Verones, F. (2020). Quantification and valuation of ecosystem services in life cycle assessment: Application of the cascade framework to rice farming systems. *Science of The Total Environment*, 747, 141278. <https://doi.org/10.1016/j.scitotenv.2020.141278>
- Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. *Annual Review of Environment and Resources*, 34(1), 179–204. <https://doi.org/10.1146/annurev.envIRON.041008.093740>
- Loladze, I., 2014. Hidden shift of the ionome of plants exposed to elevated CO₂ depletes minerals at the base of human nutrition. *elife*, 3, p.e02245.
- Lollato, R. P., Bavia, G. P., Perin, V., Knapp, M., Santos, E. A., Patrignani, A., & DeWolf, E. D. (2020). Climate-risk assessment for winter wheat using long-term weather data. *Agronomy Journal*, 112(3), 2132–2151. <https://doi.org/10.1002/agj2.20168>
- Lollato, R.P., Edwards, J.T. and Ochsner, T.E., 2017. Meteorological limits to winter wheat productivity in the US southern Great Plains. *Field Crops Research*, 203, pp.212-226.
- Lollato, R.P., Figueiredo, B.M., Dhillon, J.S., Arnall, D.B. and Raun, W.R., 2019. Wheat grain yield and grain-nitrogen relationships as affected by N, P, and K fertilization: A synthesis of long-term experiments. *Field Crops Research*, 236, pp.42-57.
- Lollato, R.P., Jaenisch, B.R. and Silva, S.R., 2021. Genotype-specific nitrogen uptake dynamics and fertilizer management explain contrasting wheat protein concentration. *Crop Science*, 61(3), pp.2048-2066.
- Lollato, R.P., Ruiz Diaz, D.A., DeWolf, E., Knapp, M., Peterson, D.E. and Fritz, A.K., 2019. Agronomic practices for reducing wheat yield gaps: a quantitative appraisal of progressive producers. *Crop Science*, 59(1), pp.333-350.
- Lundie, S., Huijbregts, M. A. J., Rowley, H. V., Mohr, N. J., & Feitz, A. J. (2007). Australian characterisation factors and normalisation figures for human toxicity and ecotoxicity. *Journal of Cleaner Production*, 15(8–9), 819–832. <https://doi.org/10.1016/j.jclepro.2006.06.019>
- Luo, Y., Fu, H., & Traore, S. (2014). Biodiversity Conservation in Rice Paddies in China: Toward Ecological Sustainability. *Sustainability*, 6(9), Article 9. <https://doi.org/10.3390/su6096107>
- Maeoka, R.E., Sadras, V.O., Ciampitti, I.A., Diaz, D.R., Fritz, A.K. and Lollato, R.P., 2020. Changes in the phenotype of winter wheat varieties released between 1920 and 2016 in response to in-furrow fertilizer: biomass allocation, yield, and grain protein concentration. *Frontiers in plant science*, 10, p.1786.
- Majumder, S., Datta, K., & Datta, S. K. (2019). Rice Biofortification: High Iron, Zinc, and Vitamin-A to Fight against “Hidden Hunger.” *Agronomy*, 9(12), Article 12. <https://doi.org/10.3390/agronomy9120803>

- Margni, M., Rossier, D., Crettaz, P., & Jolliet, O. (2002). Life cycle impact assessment of pesticides on human health and ecosystems. *Agriculture, Ecosystems & Environment*, 93(1–3), 379–392. [https://doi.org/10.1016/S0167-8809\(01\)00336-X](https://doi.org/10.1016/S0167-8809(01)00336-X)
- Marin, F.R., Zanon, A.J., Monzon, J.P., Andrade, J.F., Silva, E.H., Richter, G.L., Antolin, L.A., Ribeiro, B.S., Ribas, G.G., Battisti, R. and Heinemann, A.B., 2022. Protecting the Amazon forest and reducing global warming via agricultural intensification. *Nature Sustainability*, 5(12), pp.1018-1026.
- Masuda, K. (2016). Measuring eco-efficiency of wheat production in Japan: A combined application of life cycle assessment and data envelopment analysis. *Journal of Cleaner Production*, 126, 373–381. <https://doi.org/10.1016/j.jclepro.2016.03.090>
- Mayer, F. D., Brondani, M., Vasquez Carrillo, M. C., Hoffmann, R., & Silva Lora, E. E. (2020). Revisiting energy efficiency, renewability, and sustainability indicators in biofuels life cycle: Analysis and standardization proposal. *Journal of Cleaner Production*, 252, 119850. <https://doi.org/10.1016/j.jclepro.2019.119850>
- Mayer, J., Gunst, L., Mäder, P., Samson, M.-F., Carcea, M., Narducci, V., Thomsen, I. K., & Dubois, D. (2015). “Productivity, quality and sustainability of winter wheat under long-term conventional and organic management in Switzerland.” *European Journal of Agronomy*, 65, 27–39. <https://doi.org/10.1016/j.eja.2015.01.002>
- Mazac, R., Renwick, K., Seed, B., & Black, J. L. (2021). An Approach for Integrating and Analyzing Sustainability in Food-Based Dietary Guidelines. *Frontiers in Sustainable Food Systems*, 5. <https://www.frontiersin.org/articles/10.3389/fsufs.2021.544072>
- McKenzie, S. (2004). Social Sustainability: Towards Some Definitions. 31.
- Mebratu, D. (1998). Sustainability and sustainable development. *Environmental Impact Assessment Review*, 18(6), 493–520. [https://doi.org/10.1016/S0195-9255\(98\)00019-5](https://doi.org/10.1016/S0195-9255(98)00019-5)
- Meier, M. S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., & Stolze, M. (2015). Environmental impacts of organic and conventional agricultural products – Are the differences captured by life cycle assessment? *Journal of Environmental Management*, 149, 193–208. <https://doi.org/10.1016/j.jenvman.2014.10.006>
- Meisterling, K., Samaras, C., & Schweizer, V. (2009). Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production*, 17(2), 222–230. <https://doi.org/10.1016/j.jclepro.2008.04.009>
- Mhamdi, N., Darej, C., Mhamdi, H., Attia, K., Lanouar, L., Chouchen, R., Sadkaoui, G., & Abbes, A. (2017). Assessment of Sustainability of Smallholder Beef Cattle Farms in the North of Tunisia. *Journal of Animal Research and Nutrition*, 02(01). <https://doi.org/10.21767/2572-5459.100023>

- Miller, N.J., Griffin, T.W., Bergtold, J., Ciampitti, I.A. and Sharda, A., 2017. Farmers' adoption path of precision agriculture technology. *Advances in Animal Biosciences*, 8(2), pp.708-712.
- Miner, G.L., Delgado, J.A., Ippolito, J.A., Johnson, J.J., Kluth, D.L. and Stewart, C.E., 2022. Wheat grain micronutrients and relationships with yield and protein in the US Central Great Plains. *Field Crops Research*, 279, p.108453.
- Miniotti, E. F., Romani, M., Said-Pullicino, D., Facchi, A., Bertora, C., Peyron, M., Sacco, D., Bischetti, G. B., Lerda, C., Tenni, D., Gandolfi, C., & Celi, L. (2016). Agro-environmental sustainability of different water management practices in temperate rice agro-ecosystems. *Agriculture, Ecosystems & Environment*, 222, 235–248. <https://doi.org/10.1016/j.agee.2016.02.010>
- Miransari, M., & Smith, D. (2019). Sustainable wheat (*Triticum aestivum* L.) production in saline fields: A review. *Critical Reviews in Biotechnology*, 39(8), 999–1014. <https://doi.org/10.1080/07388551.2019.1654973>
- Mishra, A. K., Pede, V. O., Arouna, A., Labarta, R., Andrade, R., Veettil, P. C., Bhandari, H., Laborte, A. G., Balie, J., & Bouman, B. (2022). Helping feed the world with rice innovations: CGIAR research adoption and socioeconomic impact on farmers. *Global Food Security*, 33, 100628. <https://doi.org/10.1016/j.gfs.2022.100628>
- Mohammadi, A., Rafiee, S., Jafari, A., Dalgaard, T., Knudsen, M. T., Keyhani, A., Mousavi-Avval, S. H., & Hermansen, J. E. (2013). Potential greenhouse gas emission reductions in soybean farming: A combined use of Life Cycle Assessment and Data Envelopment Analysis. *Journal of Cleaner Production*, 54, 89–100. <https://doi.org/10.1016/j.jclepro.2013.05.019>
- Monteleone, M., Cammerino, A. R. B., Garofalo, P., & Delivand, M. K. (2015). Straw-to-soil or straw-to-energy? An optimal trade off in a long term sustainability perspective. *Applied Energy*, 154, 891–899. <https://doi.org/10.1016/j.apenergy.2015.04.108>
- Moore, K. J., & Dixon, P. M. (2015). Analysis of Combined Experiments Revisited. *Agronomy Journal*, 107(2), 763–771. <https://doi.org/10.2134/agronj13.0485>
- Morelli, J. (2011). Environmental Sustainability: A Definition for Environmental Professionals. *Journal of Environmental Sustainability*, 1(1), 1–10. <https://doi.org/10.14448/jes.01.0002>
- Moreno-García, B., Coronel, E., Reavis, C. W., Suvočarev, K., & Runkle, B. R. K. (2021). Environmental sustainability assessment of rice management practices using decision support tools. *Journal of Cleaner Production*, 315, 128135. <https://doi.org/10.1016/j.jclepro.2021.128135>
- Mouratiadou, I., Latka, C., van der Hilst, F., Müller, C., Berges, R., Bodirsky, B. L., Ewert, F., Faye, B., Heckeley, T., Hoffmann, M., Lehtonen, H., Lorite, I. J., Nendel, C., Palosuo, T., Rodríguez, A., Rötter, R. P., Ruiz-Ramos, M., Stella, T., Webber, H., & Wicke, B. (2021). Quantifying sustainable intensification of agriculture: The contribution of metrics

- and modelling. *Ecological Indicators*, 129, 107870.
<https://doi.org/10.1016/j.ecolind.2021.107870>
- Mudgil, D., Barak, S., & Khatkar, B. S. (2016). Optimization of bread firmness, specific loaf volume and sensory acceptability of bread with soluble fiber and different water levels. *Journal of Cereal Science*, 70, 186–191. <https://doi.org/10.1016/j.jcs.2016.06.009>
- Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, 490(7419), Article 7419. <https://doi.org/10.1038/nature11420>
- Mullen, R.W., Freeman, K.W., Raun, W.R., Johnson, G.V., Stone, M.L. and Solie, J.B., 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. *Agronomy Journal*, 95(2), pp.347-351.
- Munaro, L. B., Hefley, T. J., DeWolf, E., Haley, S., Fritz, A. K., Zhang, G., Haag, L. A., Schlegel, A. J., Edwards, J. T., Marburger, D., Alderman, P., Jones-Diamond, S. M., Johnson, J., Lingenfelter, J. E., Unêda-Trevisoli, S. H., & Lollato, R. P. (2020). Exploring long-term variety performance trials to improve environment-specific genotype × management recommendations: A case-study for winter wheat. *Field Crops Research*, 255, 107848. <https://doi.org/10.1016/j.fcr.2020.107848>
- Mungkung, R., Sitthikitpanya, S., Chaichana, R., Bamrungwong, K., Santitaweeroek, Y., Jakrawatana, N., Silalertruksa, T., & Gheewala, S. H. (2022). Measuring sustainability performance of rice cultivation in Thailand using Sustainable Rice Platform indicators. *International Journal of Agricultural Sustainability*, 20(7), 1278–1293. <https://doi.org/10.1080/14735903.2022.2105008>
- Muralikrishna, I. V., & Manickam, V. (2017). Chapter Two—Sustainable Development. In I. V. Muralikrishna & V. Manickam (Eds.), *Environmental Management* (pp. 5–21). Butterworth-Heinemann. <https://doi.org/10.1016/B978-0-12-811989-1.00002-6>
- Mustafa, G., Mahmood, H., & Iqbal, A. (2021). Environmentally friendly farming and yield of wheat crop: A case of developing country. *Journal of Cleaner Production*, 314, 127978. <https://doi.org/10.1016/j.jclepro.2021.127978>
- Mustafa, M. A., Mabhaudhi, T., & Massawe, F. (2021). Building a resilient and sustainable food system in a changing world – A case for climate-smart and nutrient dense crops. *Global Food Security*, 28, 100477. <https://doi.org/10.1016/j.gfs.2020.100477>
- Musumba, M., Grabowski, P., Palm, C., & Snapp, S. (2017). Guide for the Sustainable Intensification Assessment Framework. SSRN Electronic Journal. <https://doi.org/10.2139/ssrn.3906994>
- My, N. H. D., Demont, M., Van Loo, E. J., de Guia, A., Rutsaert, P., Tuan, T. H., & Verbeke, W. (2018). What is the value of sustainably-produced rice? Consumer evidence from experimental auctions in Vietnam. *Food Policy*, 79, 283–296. <https://doi.org/10.1016/j.foodpol.2018.08.004>

- Nadi, F., Shahi, T., & Chasiotis, V. (2022). Environmental, energy, and economic assessment of bread-making processes: A case study. *Environmental Progress & Sustainable Energy*, 41(6), e13891. <https://doi.org/10.1002/ep.13891>
- Nawaz, A., Rehman, A. U., Rehman, A., Ahmad, S., Siddique, K. H. M., & Farooq, M. (2022). Increasing sustainability for rice production systems. *Journal of Cereal Science*, 103, 103400. <https://doi.org/10.1016/j.jcs.2021.103400>
- Nguyen-Van-Hung, Sander, B. O., Quilty, J., Balingbing, C., Castalone, A. G., Romasanta, R., Alberto, M. C. R., Sandro, J. M., Jamieson, C., & Gummert, M. (2019). An assessment of irrigated rice production energy efficiency and environmental footprint with in-field and off-field rice straw management practices. *Scientific Reports*, 9(1), 16887. <https://doi.org/10.1038/s41598-019-53072-x>
- Niero, M., Ingvordsen, C. H., Hauschild, M. Z., & Bagger Jørgensen, R. (2015). LCA as a decision support tool in policy making: the case study of Danish spring barley production in a changed climate. In S. Scalbi, A. D. Loprieno, & P. Sposato (Eds.), Proceedings. International conference on Life Cycle Assessment as reference methodology for assessing supply chains and supporting global sustainability challenges: LCA for "Feeding the planet and energy for life" (pp. 101-104). ENEA.
- Notarnicola, B., Tassielli, G., Renzulli, P. A., & Monforti, F. (2017). Energy flows and greenhouses gases of EU (European Union) national breads using an LCA (Life Cycle Assessment) approach. *Journal of Cleaner Production*, 140, 455–469. <https://doi.org/10.1016/j.jclepro.2016.05.150>
- Nunes, F. A., Seferin, M., Maciel, V. G., Flores, S. H., & Ayub, M. A. Z. (2016). Life cycle greenhouse gas emissions from rice production systems in Brazil: A comparison between minimal tillage and organic farming. *Journal of Cleaner Production*, 139, 799–809. <https://doi.org/10.1016/j.jclepro.2016.08.106>
- Oberč, B. P., & Schnell, A. A. (2020). Approaches to sustainable agriculture. IUCN. <https://portals.iucn.org/library/node/49054>
- Ofori, E., Griffin, T. and Yeager, E., 2020. Duration analyses of precision agriculture technology adoption: what's influencing farmers' time-to-adoption decisions?. *Agricultural Finance Review*, 80(5), pp.647-664.
- Okpiaifo, G., Durand-Morat, A., West, G. H., Nalley, L. L., Nayga, R. M., & Wailes, E. J. (2020). Consumers' preferences for sustainable rice practices in Nigeria. *Global Food Security*, 24, 100345. <https://doi.org/10.1016/j.gfs.2019.100345>
- Omer, A. M. (2008). Energy, environment and sustainable development. *Renewable and Sustainable Energy Reviews*, 12(9), 2265–2300. <https://doi.org/10.1016/j.rser.2007.05.001>
- Pacini, C., Wossink, A., Giesen, G., Vazzana, C., & Huirne, R. (2003). Evaluation of sustainability of organic, integrated and conventional farming systems: A farm and field-

- scale analysis. *Agriculture, Ecosystems & Environment*, 95(1), 273–288.
[https://doi.org/10.1016/S0167-8809\(02\)00091-9](https://doi.org/10.1016/S0167-8809(02)00091-9)
- Pagani, M. A., Marti, A., & Bottega, G. (2014). Wheat Milling and Flour Quality Evaluation. In *Bakery Products Science and Technology* (pp. 17–53). John Wiley & Sons, Ltd.
<https://doi.org/10.1002/9781118792001.ch2>
- Panhwar, Q. A., Ali, A., Naher, U. A., & Memon, M. Y. (2019). Chapter 2—Fertilizer Management Strategies for Enhancing Nutrient Use Efficiency and Sustainable Wheat Production. In S. Chandran, M. R. Unni, & S. Thomas (Eds.), *Organic Farming* (pp. 17–39). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-813272-2.00002-1>
- Pannell, D. J., & Glenn, N. A. (2000). A framework for the economic evaluation and selection of sustainability indicators in agriculture. *Ecological Economics*, 33(1), 135–149.
[https://doi.org/10.1016/S0921-8009\(99\)00134-2](https://doi.org/10.1016/S0921-8009(99)00134-2)
- Paraskevopoulou, C., Theodoridis, A., Johnson, M., Ragkos, A., Arguile, L., Smith, L., Vlachos, D., & Arsenos, G. (2020). Sustainability Assessment of Goat and Sheep Farms: A Comparison between European Countries. *Sustainability*, 12(8), Article 8.
<https://doi.org/10.3390/su12083099>
- Parry, M. A. J., & Hawkesford, M. J. (2010). Food security: Increasing yield and improving resource use efficiency. *Proceedings of the Nutrition Society*, 69(4), 592–600.
<https://doi.org/10.1017/S0029665110003836>
- Patrignani, A., Lollato, R. P., Ochsner, T. E., Godsey, C. B., & Edwards, Jeff. T. (2014). Yield Gap and Production Gap of Rainfed Winter Wheat in the Southern Great Plains. *Agronomy Journal*, 106(4), 1329–1339. <https://doi.org/10.2134/agronj14.0011>
- Paulino-Flores, M., Martínez-Campos, Á. R., Martínez-Castañeda, F. E., López-Orona, C. A., Vizcarra-Bordi, I., & Munguía, N. (2017). Evaluation of the sustainability of hybrid and native maize production systems. *Journal of Cleaner Production*, 150, 287–293.
<https://doi.org/10.1016/j.jclepro.2017.02.182>
- Peña, N., Knudsen, M. T., Fantke, P., Antón, A., & Hermansen, J. E. (2019). Freshwater ecotoxicity assessment of pesticide use in crop production: Testing the influence of modeling choices. *Journal of Cleaner Production*, 209, 1332–1341.
<https://doi.org/10.1016/j.jclepro.2018.10.257>
- Peramaiyan, P., Craufurd, P., Kumar, V., Seelan, L. P., McDonald, A. J., Balwinder-Singh, Kishore, A., & Singh, S. (2022). Agronomic Biofortification of Zinc in Rice for Diminishing Malnutrition in South Asia. *Sustainability*, 14(13), Article 13.
<https://doi.org/10.3390/su14137747>
- Peterson, T., Paul, P.A. and Lindsey, L.E., 2023. Effect of traditional and intensive management on soft red winter wheat yield and profitability. *Agronomy Journal*, 115(3), pp.1279-1294.

- Phélinas, P., & Choumert, J. (2017). Is GM Soybean Cultivation in Argentina Sustainable? *World Development*, 99, 452–462. <https://doi.org/10.1016/j.worlddev.2017.05.033>
- Pintér, L., Hardi, P., Martinuzzi, A., & Hall, J. (2012). Bellagio STAMP: Principles for sustainability assessment and measurement. *Ecological Indicators*, 17, 20–28. <https://doi.org/10.1016/j.ecolind.2011.07.001>
- Pittelkow, C. M., Adviento-Borbe, M. A., Hill, J. E., Six, J., van Kessel, C., & Linquist, B. A. (2013). Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agriculture, Ecosystems & Environment*, 177, 10–20. <https://doi.org/10.1016/j.agee.2013.05.011>
- Pittelkow, C. M., Zorrilla, G., Terra, J., Riccetto, S., Macedo, I., Bonilla, C., & Roel, A. (2016). Sustainability of rice intensification in Uruguay from 1993 to 2013. *Global Food Security*, 9, 10–18. <https://doi.org/10.1016/j.gfs.2016.05.003>
- Popoola, J. O., Aworunse, O. S., Ojuederie, O. B., Adewale, B. D., Ajani, O. C., Oyatomi, O. A., Eruemulor, D. I., Adegboyega, T. T., & Obembe, O. O. (2022). The Exploitation of Orphan Legumes for Food, Income, and Nutrition Security in Sub-Saharan Africa. *Frontiers in Plant Science*, 13. <https://www.frontiersin.org/articles/10.3389/fpls.2022.782140>
- Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, 6(3), 317–327. <https://doi.org/10.1046/j.1365-2486.2000.00308.x>
- Pretty, J. N. (1997). The sustainable intensification of agriculture. *Natural Resources Forum*, 21(4), 247–256. <https://doi.org/10.1111/j.1477-8947.1997.tb00699.x>
- Pretty, J. N. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), 447–465. <https://doi.org/10.1098/rstb.2007.2163>
- Puhr, D. P., & D'Appolonia, B. L. (1992). Effect of Baking Absorption on Bread Yield, Crumb Moisture, and Crumb Water Activity. *Cereal Chemistry*, 69(5), 582–586.
- Quinn, D. and Steinke, K., 2019. Soft red and white winter wheat response to input-intensive management. *Agronomy Journal*, 111(1), pp.428–439.
- Ragsdale, D., Landis, D., Brodeur, J., Heimpel, G., & Desneux, N. (2011). Ecology and Management of the Soybean Aphid in North America. *Annual Review of Entomology*, 56, 375–399. <https://doi.org/10.1146/annurev-ento-120709-144755>
- Rahman, M. H. A., Chen, S. S., Razak, P. R. A., Bakar, N. A. A., Shahrun, M. S., Zin Zawawi, N., Muhamad Mujab, A. A., Abdullah, F., Jumat, F., Kamaruzaman, R., Saidon, S. A., & Abdul Talib, S. A. (2019). Life cycle assessment in conventional rice farming system: Estimation of greenhouse gas emissions using cradle-to-gate approach. *Journal of Cleaner Production*, 212, 1526–1535. <https://doi.org/10.1016/j.jclepro.2018.12.062>

- Rahman, M. R., & Bulbul, S. H. (2015). Adoption of Water Saving Irrigation Techniques for Sustainable Rice Production in Bangladesh. *Environment and Ecology Research*, 3(1), 1–8. <https://doi.org/10.13189/eer.2015.030101>
- Raj, A. S., Siliveru, K., McLean, R., Prasad, P. V. V., & Lollato, R. P. (2023). Intensive management simultaneously reduces yield gaps and improves milling and baking properties of bread wheat. *Crop Science*, 63(2), 936–955. <https://doi.org/10.1002/csc2.20906>
- Rao, N. H., & Rogers, P. P. (2006). Assessment of agricultural sustainability. *Current Science*, 91(4), 439–448.
- Raucci, G. S., Moreira, C. S., Alves, P. A., Mello, F. F. C., Frazão, L. de A., Cerri, C. E. P., & Cerri, C. C. (2015). Greenhouse gas assessment of Brazilian soybean production: A case study of Mato Grosso State. *Journal of Cleaner Production*, 96, 418–425. <https://doi.org/10.1016/j.jclepro.2014.02.064>
- Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Mullen, R.W., Freeman, K.W., Thomason, W.E. and Lukina, E.V., 2001. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. *Agronomy Journal*, 94(4), pp.815-820.
- Reay, D. S., Davidson, E. A., Smith, K. A., Smith, P., Melillo, J. M., Dentener, F., & Crutzen, P. J. (2012). Global agriculture and nitrous oxide emissions. *Nature Climate Change*, 2(6), Article 6. <https://doi.org/10.1038/nclimate1458>
- Reich, J., Paul, S.S. and Snapp, S.S., 2021. Highly variable performance of sustainable intensification on smallholder farms: A systematic review. *Global Food Security*, 30, p.100553.
- Riedesel, L., Laidig, F., Hadasch, S., Rentel, D., Hackauf, B., Piepho, H.-P., & Feike, T. (2022). Breeding progress reduces carbon footprints of wheat and rye. *Journal of Cleaner Production*, 377, 134326. <https://doi.org/10.1016/j.jclepro.2022.134326>
- Rodriguez, M. C., Sautua, F., Scandiani, M., Carmona, M., & Asurmendi, S. (2021). Current recommendations and novel strategies for sustainable management of soybean sudden death syndrome. *Pest Management Science*, 77(10), 4238–4248. <https://doi.org/10.1002/ps.6458>
- Röös, E., Fischer, K., Tidåker, P., & Nordström Källström, H. (2019). How well is farmers' social situation captured by sustainability assessment tools? A Swedish case study. *International Journal of Sustainable Development & World Ecology*, 26(3), 268–281. <https://doi.org/10.1080/13504509.2018.1560371>
- Roth, M.G., Mourtzinis, S., Gaska, J.M., Mueller, B., Roth, A., Smith, D.L. and Conley, S.P., 2021. Wheat grain and straw yield, grain quality, and disease benefits associated with increased management intensity. *Agronomy Journal*, 113(1), pp.308-320.

- Rotili, D. H., de Voil, P., Eyre, J., Serafin, L., Aisthorpe, D., Maddonni, G. Á., & Rodríguez, D. (2020). Untangling genotype x management interactions in multi-environment on-farm experimentation. *Field Crops Research*, 255, 107900. <https://doi.org/10.1016/j.fcr.2020.107900>
- Roy, R., Chan, N. W., & Rainis, R. (2014). Rice farming sustainability assessment in Bangladesh. *Sustainability Science*, 9(1), 31–44. <https://doi.org/10.1007/s11625-013-0234-4>
- Rozbicki, J., Ceglińska, A., Gozdowski, D., Jakubczak, M., Cacak-Pietrzak, G., Mądry, W., Golba, J., Piechociński, M., Sobczyński, G., Studnicki, M., & Drzazga, T. (2015). Influence of the cultivar, environment and management on the grain yield and bread-making quality in winter wheat. *Journal of Cereal Science*, 61, 126–132. <https://doi.org/10.1016/j.jcs.2014.11.001>
- RStudio Team. (2020). *RStudio: Integrated Development for R* [Computer software]. RStudio, PBC, Boston, MA. <http://www.rstudio.com/>
- Sadeghi, S. H., Sharifi Moghadam, E., Delavar, M., & Zarghami, M. (2020). Application of water-energy-food nexus approach for designating optimal agricultural management pattern at a watershed scale. *Agricultural Water Management*, 233, 106071. <https://doi.org/10.1016/j.agwat.2020.106071>
- Sadeghi, S. M., Noorhosseini, S. A., & Damalas, C. A. (2018). Environmental sustainability of corn (*Zea mays* L.) production on the basis of nitrogen fertilizer application: The case of Lahijan, Iran. *Renewable and Sustainable Energy Reviews*, 95, 48–55. <https://doi.org/10.1016/j.rser.2018.07.005>
- Sadras, V., Calderini, D. and Connor, D., 2009. Sustainable agriculture and crop physiology. In: Sadras, V., Calderini, D. (ed./s), pp.1-20. Academic Press. ISBN: 9780123744319
- Safa, M., & Samarasinghe, S. (2011). Determination and modelling of energy consumption in wheat production using neural networks: “A case study in Canterbury province, New Zealand.” *Energy*, 36(8), 5140–5147. <https://doi.org/10.1016/j.energy.2011.06.016>
- Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological Economics*, 119, 314–325. <https://doi.org/10.1016/j.ecolecon.2015.09.015>
- Salas-Reyes, I. G., Arriaga-Jordán, C. M., Rebollar-Rebollar, S., García-Martínez, A., & Albarrán-Portillo, B. (2015). Assessment of the sustainability of dual-purpose farms by the IDEA method in the subtropical area of central Mexico. *Tropical Animal Health and Production*, 47(6), 1187–1194. <https://doi.org/10.1007/s11250-015-0846-z>
- Salim, N., & Raza, A. (2020). Nutrient use efficiency (NUE) for sustainable wheat production: A review. *Journal of Plant Nutrition*, 43(2), 297–315. <https://doi.org/10.1080/01904167.2019.1676907>

- Sapirstein, H., Wu, Y., Koksel, F., & Graf, R. (2018). A study of factors influencing the water absorption capacity of Canadian hard red winter wheat flour. *Journal of Cereal Science*, 81, 52–59. <https://doi.org/10.1016/j.jcs.2018.01.012>
- Saray, M. H., Baubekova, A., Gohari, A., Eslamian, S. S., Klove, B., & Haghighi, A. T. (2022). Optimization of Water-Energy-Food Nexus considering CO₂ emissions from cropland: A case study in northwest Iran. *Applied Energy*, 307, 118236. <https://doi.org/10.1016/j.apenergy.2021.118236>
- Savary, S., Horgan, F., Willocquet, L., & Heong, K. L. (2012). A review of principles for sustainable pest management in rice. *Crop Protection*, 32, 54–63. <https://doi.org/10.1016/j.cropro.2011.10.012>
- Schaller, N. (1993). The concept of agricultural sustainability. *Agriculture, Ecosystems & Environment*, 46(1–4), 89–97. [https://doi.org/10.1016/0167-8809\(93\)90016-I](https://doi.org/10.1016/0167-8809(93)90016-I)
- Scharf, P.C., Shannon, D.K., Palm, H.L., Sudduth, K.A., Drummond, S.T., Kitchen, N.R., Mueller, L.J., Hubbard, V.C. and Oliveira, L.F., 2011. Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. *Agronomy Journal*, 103(6), pp.1683-1691.
- Schauberger, B., Ben-Ari, T., Makowski, D., Kato, T., Kato, H., & Ciais, P. (2018). Yield trends, variability and stagnation analysis of major crops in France over more than a century. *Scientific Reports*, 8(1), Article 1. <https://doi.org/10.1038/s41598-018-35351-1>
- Schmidt, J. H. (2010). Comparative life cycle assessment of rapeseed oil and palm oil. *The International Journal of Life Cycle Assessment*, 15(2), 183–197. <https://doi.org/10.1007/s11367-009-0142-0>
- Schönhofen, A., Zhang, X., & Dubcovsky, J. (2017). Combined mutations in five wheat STARCH BRANCHING ENZYME II genes improve resistant starch but affect grain yield and bread-making quality. *Journal of Cereal Science*, 75, 165–174. <https://doi.org/10.1016/j.jcs.2017.03.028>
- Schwalbert, R.A., Amado, T.J.C., Reimche, G.B. and Gebert, F., 2018. Fine-tuning of wheat (*Triticum aestivum*, L.) variable nitrogen rate by combining crop sensing and management zones approaches in southern Brazil. *Precision Agriculture*, 20, pp.56-77.
- Sciarresi, C., Patrignani, A., Soltani, A., Sinclair, T. and Lollato, R.P., 2019. Plant traits to increase winter wheat yield in semiarid and subhumid environments. *Agronomy Journal*, 111(4), pp.1728-1740.
- Sentelhas, P. C., Battisti, R., Câmara, G. M. S., Farias, J. R. B., Hampf, A. C., & Nendel, C. (2015). The soybean yield gap in Brazil – magnitude, causes and possible solutions for sustainable production. *The Journal of Agricultural Science*, 153(8), 1394–1411. <https://doi.org/10.1017/S0021859615000313>

- Seymour, M., Kirkegaard, J. A., Peoples, M. B., White, P. F., French, R. J., Seymour, M., Kirkegaard, J. A., Peoples, M. B., White, P. F., & French, R. J. (2012). Break-crop benefits to wheat in Western Australia – insights from over three decades of research. *Crop and Pasture Science*, 63(1), 1–16. <https://doi.org/10.1071/CP11320>
- Shamsi, K. B. A., Guarnaccia, P., Cosentino, S. L., Leonardi, C., Caruso, P., Stella, G., & Timpanaro, G. (2019). Analysis of Relationships and Sustainability Performance in Organic Agriculture in the United Arab Emirates and Sicily (Italy). *Resources*, 8(1), Article 1. <https://doi.org/10.3390/resources8010039>
- Sharma, A., Singh, G., & Arya, S. K. (2020). Biofuel from rice straw. *Journal of Cleaner Production*, 277, 124101. <https://doi.org/10.1016/j.jclepro.2020.124101>
- Sheoran, S., Kumar, S., Ramtekey, V., Kar, P., Meena, R. S., & Jangir, C. K. (2022). Current Status and Potential of Biofortification to Enhance Crop Nutritional Quality: An Overview. *Sustainability*, 14(6), Article 6. <https://doi.org/10.3390/su14063301>
- Shewry, P.R. and Hey, S.J., 2015. The contribution of wheat to human diet and health. *Food and energy security*, 4(3), pp.178-202.
- Shi, Y., Huang, G., An, C., Zhou, Y., & Yin, J. (2021). Assessment of regional greenhouse gas emissions from spring wheat cropping system: A case study of Saskatchewan in Canada. *Journal of Cleaner Production*, 301, 126917. <https://doi.org/10.1016/j.jclepro.2021.126917>
- Shrestha, P., Karim, R. A., Sieverding, H. L., Archer, D. W., Kumar, S., Nleya, T., Graham, C. J., & Stone, J. J. (2020). Life cycle assessment of wheat production and wheat-based crop rotations. *Journal of Environmental Quality*, 49(6), 1515–1529. <https://doi.org/10.1002/jeq2.20158>
- Shukla, P. R., & Skea, J. (2022). Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.
- Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., & Malley, J. (Eds.). (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. <https://doi.org/10.1017/9781009157926>
- Silva, J.V., Reidsma, P., Baudron, F., Laborte, A.G., Giller, K.E. and van Ittersum, M.K., 2021. How sustainable is sustainable intensification? Assessing yield gaps at field and farm level across the globe. *Global Food Security*, 30, p.100552.
- Simpson, G. B., Jewitt, G. P. W., Becker, W., Badenhorst, J., Masia, S., Neves, A. R., Rovira, P., & Pascual, V. (2022). The Water-Energy-Food Nexus Index: A Tool to Support Integrated Resource Planning, Management and Security. *Frontiers in Water*, 4, 825854. <https://doi.org/10.3389/frwa.2022.825854>

- Singh, G., Gupta, M. K., Chaurasiya, S., Sharma, V. S., & Pimenov, D. Y. (2021). Rice straw burning: A review on its global prevalence and the sustainable alternatives for its effective mitigation. *Environmental Science and Pollution Research*, 28(25), 32125–32155. <https://doi.org/10.1007/s11356-021-14163-3>
- Slätmo, E., Fischer, K., & Rööös, E. (2017). The Framing of Sustainability in Sustainability Assessment Frameworks for Agriculture. *Sociologia Ruralis*, 57(3), 378–395. <https://doi.org/10.1111/soru.12156>
- Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., & Glover, J. (2017). Measuring sustainable intensification in smallholder agroecosystems: A review. *Global Food Security*, 12, 127–138. <https://doi.org/10.1016/j.gfs.2016.11.002>
- Smith, L. G., Westaway, S., Mullender, S., Ghaley, B. B., Xu, Y., Lehmann, L. M., Pisanelli, A., Russo, G., Borek, R., Wawer, R., Borzęcka, M., Sandor, M., Gliga, A., & Smith, J. (2022). Assessing the multidimensional elements of sustainability in European agroforestry systems. *Agricultural Systems*, 197, 103357. <https://doi.org/10.1016/j.agsy.2021.103357>
- Smith, V. H., & Schindler, D. W. (2009). Eutrophication science: Where do we go from here? *Trends in Ecology & Evolution*, 24(4), 201–207. <https://doi.org/10.1016/j.tree.2008.11.009>
- Soam, S., Borjesson, P., Sharma, P. K., Gupta, R. P., Tuli, D. K., & Kumar, R. (2017). Life cycle assessment of rice straw utilization practices in India. *Bioresource Technology*, 228, 89–98. <https://doi.org/10.1016/j.biortech.2016.12.082>
- Song, X., Wang, X., Li, X., Zhang, W., & Scheffran, J. (2021). Policy-oriented versus market-induced: Factors influencing crop diversity across China. *Ecological Economics*, 190, 107184.
- Ssebunya, B. R., Schmid, E., Asten, P. van, Schader, C., Altenbuchner, C., & Stolze, M. (2017). Stakeholder engagement in prioritizing sustainability assessment themes for smallholder coffee production in Uganda. *Renewable Agriculture and Food Systems*, 32(5), 428–445. <https://doi.org/10.1017/S1742170516000363>
- Stuart, A. M., Devkota, K. P., Sato, T., Pame, A. R. P., Balingbing, C., My Phung, N. T., Kieu, N. T., Hieu, P. T. M., Long, T. H., Beebout, S., & Singleton, G. R. (2018). On-farm assessment of different rice crop management practices in the Mekong Delta, Vietnam, using sustainability performance indicators. *Field Crops Research*, 229, 103–114. <https://doi.org/10.1016/j.fcr.2018.10.001>
- Stuart, A. M., Pame, A. R. P., Vithoonjit, D., Viriyangkura, L., Pithuncharurnlap, J., Meesang, N., Suksiri, P., Singleton, G. R., & Lampayan, R. M. (2018). The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand. *Field Crops Research*, 220, 78–87. <https://doi.org/10.1016/j.fcr.2017.02.005>

- Taghavifar, H., & Mardani, A. (2015). Energy consumption analysis of wheat production in West Azarbayjan utilizing life cycle assessment (LCA). *Renewable Energy*, 74, 208–213. <https://doi.org/10.1016/j.renene.2014.08.026>
- Taki, M., Soheili-Fard, F., Rohani, A., Chen, G., & Yildizhan, H. (2018). Life cycle assessment to compare the environmental impacts of different wheat production systems. *Journal of Cleaner Production*, 197, 195–207. <https://doi.org/10.1016/j.jclepro.2018.06.173>
- Tamagno, S., Eagle, A. J., McLellan, E. L., van Kessel, C., Linnquist, B. A., Ladha, J. K., & Pittelkow, C. M. (2022). Quantifying N leaching losses as a function of N balance: A path to sustainable food supply chains. *Agriculture, Ecosystems & Environment*, 324, 107714. <https://doi.org/10.1016/j.agee.2021.107714>
- Teuscher, P., Grüniger, B., & Ferdinand, N. (2006). Risk management in sustainable supply chain management (SSCM): Lessons learnt from the case of GMO-free soybeans. *Corporate Social Responsibility and Environmental Management*, 13(1), 1–10. <https://doi.org/10.1002/csr.81>
- Thapa, S., Bhandari, A., Ghimire, R., Xue, Q., Kidwaro, F., Ghatrehsamani, S., Maharjan, B., & Goodwin, M. (2021). Managing Micronutrients for Improving Soil Fertility, Health, and Soybean Yield. *Sustainability*, 13(21), Article 21. <https://doi.org/10.3390/su132111766>
- Thomson, A.M., Ramsey, S., Barnes, E., Basso, B., Eve, M., Gennet, S., Grassini, P., Kliethermes, B., Matlock, M., McClellan, E. and Spevak, E., 2017. Science in the supply chain: collaboration opportunities for advancing sustainable agriculture in the United States. *Agricultural & Environmental Letters*, 2(1), p.170015.
- Tiammee, S., & Likasiri, C. (2020). Sustainability in corn production management: A multi-objective approach. *Journal of Cleaner Production*, 257, 120855. <https://doi.org/10.1016/j.jclepro.2020.120855>
- Tian, W., Jaenisch, B., Gui, Y., Hu, R., Chen, G., Lollato, R.P. and Li, Y., 2022. Effect of environment and field management strategies on phenolic acid profiles of hard red winter wheat genotypes. *Journal of the Science of Food and Agriculture*, 102(6), pp.2424-2431.
- Tseng, M.-C., Roel, A., Deambrosi, E., Terra, J. A., Zorrilla, G., Riccetto, S., & Pittelkow, C. M. (2020). Towards actionable research frameworks for sustainable intensification in high-yielding rice systems. *Scientific Reports*, 10(1), 9975. <https://doi.org/10.1038/s41598-020-63251-w>
- Turmel, M.-S., Speratti, A., Baudron, F., Verhulst, N., & Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. *Agricultural Systems*, 134, 6–16. <https://doi.org/10.1016/j.agry.2014.05.009>
- United Nations. (2015, September). Transforming our world: The 2030 Agenda for Sustainable Development. <https://sdgs.un.org/2030agenda>

- Upadhyay, M. K., Majumdar, A., Suresh Kumar, J., & Srivastava, S. (2020). Arsenic in Rice Agro-Ecosystem: Solutions for Safe and Sustainable Rice Production. *Frontiers in Sustainable Food Systems*, 4. <https://www.frontiersin.org/articles/10.3389/fsufs.2020.00053>
- USDA ARS. (2019). *FoodData Central*. fdc.nal.usda.gov
- USDA. (2022). Sustainability. Sustainability. <https://www.usda.gov/oce/sustainability>
- USDA-NASS. (2023). *Kansas Wheat Quality*. <https://kswheat.com/sites/default/files/2023-09/Wheat%20Quality%20USDA%20NASS.pdf>
- Vallance, S., Perkins, H. C., & Dixon, J. E. (2011). What is social sustainability? A clarification of concepts. *Geoforum*, 42(3), 342–348. <https://doi.org/10.1016/j.geoforum.2011.01.002>
- van Calker, K. J., Berentsen, P. B. M., de Boer, I. J. M., Giesen, G. W. J., & Huirne, R. B. M. (2007). Modelling worker physical health and societal sustainability at farm level: An application to conventional and organic dairy farming. *Agricultural Systems*, 94(2), 205–219. <https://doi.org/10.1016/j.agsy.2006.08.006>
- Van Groenigen, J. W., Velthof, G. L., Oenema, O., Van Groenigen, K. J., & Van Kessel, C. (2010). Towards an agronomic assessment of N₂O emissions: A case study for arable crops. *European Journal of Soil Science*, 61(6), 903–913. <https://doi.org/10.1111/j.1365-2389.2009.01217.x>
- Van Hung, N., Migo, M. V., Quilloy, R., Chivenge, P., & Gummert, M. (2020). Life Cycle Assessment Applied in Rice Production and Residue Management. In M. Gummert, N. V. Hung, P. Chivenge, & B. Douthwaite (Eds.), *Sustainable Rice Straw Management* (pp. 161–174). Springer International Publishing. https://doi.org/10.1007/978-3-030-32373-8_10
- van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Titttonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Research*, 143, 4–17. <https://doi.org/10.1016/j.fcr.2012.09.009>
- Vanlauwe, B., Hungria, M., Kanampiu, F., & Giller, K. E. (2019). The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. *Agriculture, Ecosystems & Environment*, 284, 106583. <https://doi.org/10.1016/j.agee.2019.106583>
- Veeck, G.P., Dalmago, G.A., Bremm, T., Buligon, L., Jacques, R.J.S., Fernandes, J.M., Santi, A., Vargas, P.R. and Roberti, D.R., 2022. *CO₂ flux in a wheat-soybean succession in subtropical Brazil: A carbon sink* (Vol. 51, No. 5, pp. 899-915).
- Verdi, L., Marta, A. D., Falconi, F., Orlandini, S., & Mancini, M. (2022). Comparison between organic and conventional farming systems using Life Cycle Assessment (LCA): A case study with an ancient wheat variety. *European Journal of Agronomy*, 141, 126638. <https://doi.org/10.1016/j.eja.2022.126638>

- Verma, P., & Raghubanshi, A. S. (2018). Urban sustainability indicators: Challenges and opportunities. *Ecological Indicators*, 93, 282–291. <https://doi.org/10.1016/j.ecolind.2018.05.007>
- Wagacha, J. M., & Muthomi, J. W. (2008). Mycotoxin problem in Africa: Current status, implications to food safety and health and possible management strategies. *International Journal of Food Microbiology*, 124(1), 1–12. <https://doi.org/10.1016/j.ijfoodmicro.2008.01.008>
- Wagle, P., Gowda, P. H., Northup, B. K., Neel, J. P., Starks, P. J., Turner, K. E., & Steiner, J. L. (2021). Carbon dioxide and water vapor fluxes of multi-purpose winter wheat production systems in the US Southern Great Plains. *Agricultural and Forest Meteorology*, 310, 108631.
- Wagle, P., Gowda, P.H., Manjunatha, P., Northup, B.K., Rocateli, A.C. and Taghvaeian, S., (2019). Carbon and water dynamics in co-located winter wheat and canola fields in the US Southern Great Plains. *Agricultural and Forest Meteorology*, 279, p.107714.
- Wang, C., Zhao, J., Gao, Z., Feng, Y., Laraib, I., Chen, F., & Chu, Q. (2022). Exploring wheat-based management strategies to balance agricultural production and environmental sustainability in a wheat–maize cropping system using the DNDC model. *Journal of Environmental Management*, 307, 114445. <https://doi.org/10.1016/j.jenvman.2022.114445>
- Wang, M., Xia, X., Zhang, Q., & Liu, J. (2010). Life cycle assessment of a rice production system in Taihu region, China. *International Journal of Sustainable Development & World Ecology*, 17(2), 157–161. <https://doi.org/10.1080/13504501003594224>
- Wang, T., Jin, H., Fan, Y., Obembe, O., & Li, D. (2021). Farmers’ adoption and perceived benefits of diversified crop rotations in the margins of US Corn Belt. *Journal of Environmental Management*, 293, 112903.
- WCED, (World Commission on Environment and Development). (1987). Our Common Future. Oxford University Press, New York.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, 21(9), 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>
- West, T. O., & Marland, G. (2002). A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agriculture, Ecosystems & Environment*, 91(1–3), 217–232. [https://doi.org/10.1016/S0167-8809\(01\)00233-X](https://doi.org/10.1016/S0167-8809(01)00233-X)
- Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis* (2nd ed. 2016). Springer International Publishing : Imprint: Springer. <https://doi.org/10.1007/978-3-319-24277-4>

- Wyborn, C., Datta, A., Montana, J., Ryan, M., Leith, P., Chaffin, B., Miller, C., & van Kerkhoff, L. (2019). Co-Producing Sustainability: Reordering the Governance of Science, Policy, and Practice. *Annual Review of Environment and Resources*, 44(1), 319–346. <https://doi.org/10.1146/annurev-environ-101718-033103>
- Xu, G., Luo, Y., Zhang, Y., Wang, H., Shen, Y., Liu, Y., & Shang, S. (2022). Comparison on environmental impacts of cereal and forage production in the Loess Plateau of China: Using life cycle assessment with uncertainty and variability analysis. *Journal of Cleaner Production*, 380, 135094. <https://doi.org/10.1016/j.jclepro.2022.135094>
- Yang, C., Wang, X., Li, J., Zhang, G., Shu, H., Hu, W., Han, H., Liu, R., & Guo, Z. (2023). Straw return increases crop production by improving soil organic carbon sequestration and soil aggregation in a long-term wheat-cotton cropping system. *Journal of Integrative Agriculture*, S2095311923001752. <https://doi.org/10.1016/j.jia.2023.06.009>
- Yao, Z., Zhang, W., Wang, X., Zhang, L., Zhang, W., Liu, D., & Chen, X. (2021). Agronomic, environmental, and ecosystem economic benefits of controlled-release nitrogen fertilizers for maize production in Southwest China. *Journal of Cleaner Production*, 312, 127611. <https://doi.org/10.1016/j.jclepro.2021.127611>
- Young, M. D., Ros, G. H., & de Vries, W. (2021). Impacts of agronomic measures on crop, soil, and environmental indicators: A review and synthesis of meta-analysis. *Agriculture, Ecosystems & Environment*, 319, 107551. <https://doi.org/10.1016/j.agee.2021.107551>
- Yousefi, M., Damghani, A. M., & Khoramivafa, M. (2014). Energy consumption, greenhouse gas emissions and assessment of sustainability index in corn agroecosystems of Iran. *Science of The Total Environment*, 493, 330–335. <https://doi.org/10.1016/j.scitotenv.2014.06.004>
- Yu, Y., Xue, L., & Yang, L. (2014). Winter legumes in rice crop rotations reduces nitrogen loss, and improves rice yield and soil nitrogen supply. *Agronomy for Sustainable Development*, 34(3), 633–640. <https://doi.org/10.1007/s13593-013-0173-6>
- Yuan, S., Linquist, B. A., Wilson, L. T., Cassman, K. G., Stuart, A. M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V. E., Krisnadi, L. Y., Zanon, A. J., Heinemann, A. B., Carracelas, G., Subash, N., Brahmanand, P. S., Li, T., Peng, S., & Grassini, P. (2021). Sustainable intensification for a larger global rice bowl. *Nature Communications*, 12(1), 7163. <https://doi.org/10.1038/s41467-021-27424-z>
- Yuan, S., Linquist, B.A., Wilson, L.T., Cassman, K.G., Stuart, A.M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V.E. and Krisnadi, L.Y., 2021. Sustainable intensification for a larger global rice bowl. *Nature communications*, 12(1), p.7163.
- Yuan, S., Stuart, A.M., Laborte, A.G., Rattalino Edreira, J.I., Dobermann, A., Kien, L.V.N., Thúy, L.T., Paothong, K., Traesang, P., Tint, K.M. and San, S.S., 2022. Southeast Asia must narrow down the yield gap to continue to be a major rice bowl. *Nature Food*, 3(3), pp.217-226.

- Yunlong, C., & Smit, B. (1994). Sustainability in agriculture: A general review. *Agriculture, Ecosystems & Environment*, 49(3), 299–307. [https://doi.org/10.1016/0167-8809\(94\)90059-0](https://doi.org/10.1016/0167-8809(94)90059-0)
- Zadoks, J. C., Chang, T. T., & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed research*, 14(6), 415-421
- Zahm, F., Alonso Ugaglia, A., Barbier, J.-M., Boureau, H., Carayon, D., B., D., M., G., Gasselin, P., Girard, S., Redlingshöfer, B., Guichard, L., Gestin, C., Loyce, C., Manneville, V., Rodrigues, I., & Redlingshöfer, B. (2022). Assessing the overall performance of a farm from a conceptual framework mobilizing the properties and objectives of sustainability in agriculture. The IDEA Method version 4. https://methode-idea.org/fileadmin/user_upload/Documents/OutilsRessources/Publications/2022_02_24_zahm_et_al_IDEA-v4_note_presentation.pdf
- Zahm, F., Viaux, P., Vilain, L., Girardin, P., & Mouchet, C. (2008). Assessing farm sustainability with the IDEA method—From the concept of agriculture sustainability to case studies on farms. *Sustainable Development*, 16, 271–281. <https://doi.org/10.1002/sd.380>
- Zhang, J., Blackmer, A. M., Blackmer, T. M., Kyveryga, P. M., & Ellsworth, J. W. (2007). Nitrogen deficiency and recovery in sustainable corn production as revealed by leaf chlorophyll measurements. *Agronomy for Sustainable Development*, 27(4), 313–319. <https://doi.org/10.1051/agro:2007023>
- Zhang, J., Li, W., Zhou, Y., Ding, Y., Xu, L., Jiang, Y., & Li, G. (2021). Long-term straw incorporation increases rice yield stability under high fertilization level conditions in the rice–wheat system. *The Crop Journal*, 9(5), 1191–1197. <https://doi.org/10.1016/j.cj.2020.11.007>
- Zhang, L., Zhang, W., Cui, Z., Hu, Y., Schmidhalter, U., & Chen, X. (2021). Environmental, human health, and ecosystem economic performance of long-term optimizing nitrogen management for wheat production. *Journal of Cleaner Production*, 311, 127620. <https://doi.org/10.1016/j.jclepro.2021.127620>
- Zhang, Q., Chen, S., Dong, Y., Liu, D., Yang, X., & Yang, Z. (2017). Controllability of Phosphorus Losses in Surface Runoff from Sloping Farmland Treated by Agricultural Practices. *Land Degradation & Development*, 28(5), 1704–1716. <https://doi.org/10.1002/ldr.2702>
- Zhang, S., & Zhu, D. (2020). Have countries moved towards sustainable development or not? Definition, criteria, indicators and empirical analysis. *Journal of Cleaner Production*, 267, 121929. <https://doi.org/10.1016/j.jclepro.2020.121929>
- Zhang, S., Huang, G., Zhang, Y., Lv, X., Wan, K., Liang, J., Feng, Y., Dao, J., Wu, S., Zhang, L., Yang, X., Lian, X., Huang, L., Shao, L., Zhang, J., Qin, S., Tao, D., Crews, T. E., Sacks, E. J., ... Hu, F. (2023). Sustained productivity and agronomic potential of

- perennial rice. *Nature Sustainability*, 6(1), Article 1. <https://doi.org/10.1038/s41893-022-00997-3>
- Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., Mi, G., Miao, Y., Zhang, F., & Dou, Z. (2016). Closing yield gaps in China by empowering smallholder farmers. *Nature*, 537(7622), Article 7622. <https://doi.org/10.1038/nature19368>
- Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, 528(7580), Article 7580. <https://doi.org/10.1038/nature15743>
- Zhang, Y., Cui, J., Liu, X., Liu, H., Liu, Y., Jiang, X., Li, Z., & Zhang, M. (2022). Application of water-energy-food nexus approach for optimal tillage and irrigation management in intensive wheat-maize double cropping system. *Journal of Cleaner Production*, 381, 135181. <https://doi.org/10.1016/j.jclepro.2022.135181>
- Zhao, H., Zhai, X., Guo, L., Liu, K., Huang, D., Yang, Y., Li, J., Xie, S., Zhang, C., Tang, S., & Wang, K. (2019). Assessing the efficiency and sustainability of wheat production systems in different climate zones in China using emergy analysis. *Journal of Cleaner Production*, 235, 724–732. <https://doi.org/10.1016/j.jclepro.2019.06.251>
- Zhou, G., Gao, S., Lu, Y., Liao, Y., Nie, J., & Cao, W. (2020). Co-incorporation of green manure and rice straw improves rice production, soil chemical, biochemical and microbiological properties in a typical paddy field in southern China. *Soil and Tillage Research*, 197, 104499. <https://doi.org/10.1016/j.still.2019.104499>
- Zhou, T., Chen, L., Wang, W., Xu, Y., Zhang, W., Zhang, H., Liu, L., Wang, Z., Gu, J., & Yang, J. (2022). Effects of application of rapeseed cake as organic fertilizer on rice quality at high yield level. *Journal of the Science of Food and Agriculture*, 102(5), 1832–1841. <https://doi.org/10.1002/jsfa.11518>
- Zhu, C., Kobayashi, K., Loladze, I., Zhu, J., Jiang, Q., Xu, X., Liu, G., Seneweera, S., Ebi, K.L., Drewnowski, A. and Fukagawa, N.K., 2018. Carbon dioxide (CO₂) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Science advances*, 4(5), p.eaaq1012.
- Zhuang, Y., Ruan, S., Zhang, L., Chen, J., Li, S., Wen, W., & Liu, H. (2022). Effects and potential of optimized fertilization practices for rice production in China. *Agronomy for Sustainable Development*, 42(2), 32. <https://doi.org/10.1007/s13593-022-00759-7>
- Zingale, S., Guarnaccia, P., Matarazzo, A., Lagioia, G., & Ingrao, C. (2022). A systematic literature review of life cycle assessments in the durum wheat sector. *Science of The Total Environment*, 844, 157230. <https://doi.org/10.1016/j.scitotenv.2022.157230>

Zortea, R. B., Maciel, V. G., & Passuello, A. (2018). Sustainability assessment of soybean production in Southern Brazil: A life cycle approach. *Sustainable Production and Consumption*, 13, 102–112. <https://doi.org/10.1016/j.spc.2017.11.002>

Appendix A - Chapter 1 Supplementary Material

A.1 Examples of Existing Sustainability Programs

In the age of digital agriculture, digital tools can be useful for sharing knowledge and providing a convenient means of sustainability assessment. However, some literature indicates a lack of web-based or mobile applications that quantify or address the issue of sustainability (Eichler Inwood & Dale, 2019). Most applications address specific issues within agriculture instead of integrating goals for agricultural sustainability. Nevertheless, the programs are crucial for information distribution and ease of access for sustainability metrics. Government and commercial entities are developing platforms for assessing or promoting sustainable agriculture for United States and/or for global use.

A.1.1 Government initiatives

The Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) was created under the U.S. Government's Global Hunger and Food Security Initiative in 2014. SIIL was established with intentions of advancing food and nutritional security through sustainable intensification of crop production. Through this program, the Sustainable Intensification Assessment Framework (SI Toolkit) was developed to direct sustainable intensification research through a common framework (Stewart et al., 2018). It has a wide scale from the plot level to a landscape approach, using five categories of indicators that include productivity, economic, environmental, social, and human condition.

A.1.2 Fieldprint Platform

Fieldprint Platform was first released in 2009 by Field to Market, with its most recent version released in July 2021 as Fieldprint Platform 4.0 (Field to Market, 2022). The Fieldprint

Calculator in this program allows farmers to compare the environmental sustainability of the practices they use to benchmarks determined on different spatial scales. The analysis uses eight indicators to assess performance at the field level, including water quality, irrigated water use, soil carbon, soil conservation, land use, energy use, greenhouse gas emissions, and biodiversity. A number of companies have developed programs using this platform to encourage sustainable agriculture practices to ensure sustainable product sourcing or to assess sustainability. Archer Daniels Midland (ADM), Ardent Mills, and Cargill are among the companies with the most active projects through the Fieldprint platform. Farmers who opt to share their information assist these suppliers and retailers to make sustainable decisions further in the supply chain. This program's focus is assessing environmental factors at the field level to generate information on a larger scale.

A.1.3 Cropwise Sustainability

Through their Cropwise Digital Farming platform, Syngenta released Cropwise Sustainability in February 2022 (Syngenta, 2022). This program, available as a mobile application, is a tool farmers can use to calculate the sustainability of their farm and compare their score to a community of farmers. Six categories are considered in the assessment including optimal production, water impact, soil health, biodiversity and habitat, human and animal health, and community leadership. Through the program, farmers can view practices that others in their community are using to enhance sustainability, and the results can be used for reporting sustainability to business partners.

A.1.4 ForGround

In August 2022, Bayer Corporation launched a sustainability platform under the name ForGround (Bayer, 2022). This platform is directed towards both farmers and companies

intending to improve their individual sustainability, with a direct focus on involvement in the carbon market. ForGround provides farmers with agronomic support and discounts to assist in the shift to regenerative agriculture, while involved companies are aided in entering the carbon market. The focal point of the platform is on improvements to soil health but lacks an assessment of sustainability. Integrated with the ForGround platform is the Bayer Carbon Program, in which farmers can receive compensation for the use of cover crops and reduced tillage. Programs exist internationally and include the U.S. Carbon Program, the European Carbon Program, and PRO Carbono (Brazil).

A.1.5 Earthworm

Founded in 1999, the organization now known as Earthworm works with companies around the world including several companies in the United States (Earthworm, 2022). Using a supply chain approach, the organization works with companies (e.g. Cargill, Johnson & Johnson, 3M, Nestlé, etc.) to develop goals in projects to help the company's supply chain be more sustainable. They focus specifically on preserving the world's habitats and ecosystems, individuals and groups along supply chains, and preservation of Earth's climate. 40 member companies work with Earthworm, and specific projects include work in forest conservation, soil health, and social sustainability.

A.1.6 Farm Sustainability Assessment by SAI Platform

Sustainable Agriculture Initiative Platform (SAI Platform) was created in 2002 to find solutions to the common problems of the food and drink industry and to increase the sustainability of agriculture (SAI Platform, 2022). To assist this, the Farm Sustainability Assessment (FSA) program was established in 2014. This program assesses the sustainability of specific farms for use by businesses to analyze their supply chains. FSA has been successfully

implemented in Florida orange (*Citrus sinensis*) production and sugarbeet (*Beta vulgaris*) production in Europe and Russia. In addition, many other projects have been completed through the SAI Platform in collaboration with over 170 member companies.

A.2 References

- Bayer. (2022). ForGround. <https://bayerforground.com/>
- Earthworm. (2022). A non-profit driven to positively impact people and nature. English. <https://www.earthworm.org/>
- Eichler Inwood, S. E., & Dale, V. H. (2019). State of apps targeting management for sustainability of agricultural landscapes. A review. *Agronomy for Sustainable Development*, 39(1), 8. <https://doi.org/10.1007/s13593-018-0549-8>
- SAI Platform. (2022). Farm Sustainability Assessment. Sustainable Agriculture Initiative Platform. <https://saipatform.org/fsa/>
- Syngenta. (2022, January 4). Cropwise Sustainability US. Cropwise Global. <https://www.cropwise.com/us/sustainability>
- Stewart, Z. P., Middendorf, B. J., Musumba, M., Grabowski, P., Palm, C., Snapp, S., & Prasad, P. V. V. (2018, November). Sitoolkit.com. Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification. <https://sitoolkit.com/>

Appendix B - Chapter 2 Supplementary Material

B.1 Additional Methods, Tables, and Figures

Soil samples were taken at depths of 0-15 cm and 15-60 cm prior to planting, and were subjected to several tests of soil properties and fertility. Stand counts were taken in the fall from an area of 0.19 m² to determine plant density. In the 2020-21 growing season, canopy coverage was measured using photos run the Canopeo software to determine green cover of the soil approximately three weeks after fungicide application. In the 2021-22 growing season, canopy coverage was measured at several growth stages, including Zadoks growth stages 26, 31, 60, and again at approximately three weeks after fungicide application (~Zadoks GS 90). Plant height was measured and biomass samples were collected from a 0.19 m² area just prior to harvest. Samples were dried at 65°C for dry mass determination. Whole plant weight was determined before samples were partitioned between stover and heads, both of which were then weighed again. Heads were counted and subjected to threshing to separate the seeds from the chaff, with each mass being measured and recorded. Seeds were then subject to counting and weighing to determine thousand kernel weight. Stover and chaff were ground together, and the grain was ground separately before being subject to several content tests, including total carbon and nitrogen content measured using a Leco TruSpec CN combustion analyzer; and phosphorus, potassium, and sulfur used the perchloric digest method. Following harvest, 0-60 cm soil samples were collected in each plot of three replications at each location for analysis of nitrate concentration of the soil. In addition, grain was analyzed for grain hardness.

Whole-plot grain samples were collected from the combine for milling, dough, and baking quality assessments. Wheat milling was conducted according to AACC International

Method 26-21.02 for Experimental Milling. First, samples from a treatment-variety-location combination were mixed and subsampled three times into 1500g samples for remaining analyses. The samples were tempered to 16% moisture content, and milling yield was calculated as the percentage of flour produced from the weight of tempered wheat. Flour protein was determined following AACC International Method 39-11.01 using NIR methodology. Ash content of the flour was determined following AACC International Method 08-21.01 using NIR predictions of ash content. Falling number was determined using AACC International Method 56-81.04 procedures. Dough characteristics, including dough development time, Stability, mixing tolerance index, time to breakdown, and water absorption, were determined with a farinograph using AACC International Method 54-21.01 for Physical Dough Tests. Baking quality was determined according to AACC International Method 10-10.03 using ingredient ratios for 500 grams of flour. The resulting dough was split by weight into three loafs that each contained 100 grams of flour. Each loaf contained 5.3 grams of yeast, 6.0 grams of sucrose, 1.5 grams of salt, 3.0 grams of shortening, and water based on the farinograph value for water absorption. Finally, loaf volume was measured for each loaf using rapeseed displacement methods. In addition to milling and baking quality, DON and fusarium damaged kernels were determined in ppm and kernels per 100 kernels, respectively.

Table B.1. Soil test values describing soil conditions at the time of planting at 0-15 and 15-60 cm depths.

Region	Site Name	Depth	pH	Buffer pH	NO3-N	NH4-N	Mehlich P	K	SO4-S	Ca	Cu	Mg	Mn	Na	Zn	Fe	Cl	OM	CEC	Sand	Silt	Clay
		cm			mg kg ⁻¹													%	Meq 100g ⁻¹	%	%	%
2020-21																						
Sub-Humid	Ashland Bottoms (2)	0-15	6.1	6.6	6.8	6.9	32.8	345.2	6.0	2,524.1	1.5	266.3	26.4	10.0	1.1	70.5	-	2.5	23.17	12	58	30
		15-60	6.4	6.7	5.0	6.3	20.0	314.9	6.2	2,834.0	1.6	299.1	22.0	12.4	0.7	66.6	-	2.3	23.45	8	60	32
	Ashland Bottoms (1)	0-15	5.5	6.7	11.0	5.6	30.2	224.4	5.8	1,313.0	0.9	145.1	19.5	9.8	0.9	75.1	-	1.8	14.63	26	60	14
		15-60	6.3	7.0	4.2	3.9	13.4	175.7	3.2	1,465.1	0.8	150.5	9.2	10.2	0.5	51.3	-	1.3	11.83	26	60	14
	Belleville	0-15	4.8	5.9	14.6	8.4	50.6	402.8	12.3	1,371.3	1.6	193.2	59.2	13.8	0.9	157.2	-	2.9	24.76	12	64	24
		15-60	5.4	6.2	7.8	6.2	20.6	319.3	9.2	2,033.1	1.6	267.8	27.0	24.6	0.5	116.1	-	2.6	24.52	10	60	30
	Hutchinson	0-15	4.7	5.9	8.9	5.8	71.2	212.6	11.3	896.9	1.5	181.9	52.5	19.5	0.6	138.5	-	2.1	21.62	36	42	22
		15-60	5.7	6.5	4.4	4.8	21.2	189.3	11.0	1,852.6	1.2	254.8	23.4	46.9	0.4	101.3	-	2.0	20.42	34	40	26
	Manhattan	0-15	7.4	7.2	7.5	11.6	16.2	347.4	8.2	6,064.7	1.5	229.9	15.0	14.0	0.8	43.4	-	3.9	34.05	4	60	36
		15-60	7.4	7.2	8.3	9.5	12.7	328.9	7.3	6,227.2	1.6	225.1	12.9	15.1	0.7	41.0	-	3.7	34.89	4	60	36
	Garden City	0-15	8.0	7.5	8.4	27.5	82.6	770.6	4.8	4917.7	1.0	394.4	13.7	21.4	1.2	6.3	3.0	1.6	29.94	24	48	28
		15-60	7.7	7.3	6.7	7.2	29.2	453.9	13.3	2795.2	0.8	785.0	7.5	42.0	0.4	11.7	5.8	1.6	21.86	26	44	30
	Leoti	0-15	6.8	7.0	16.2	5.9	118.6	793.2	7.1	2,497.2	1.4	324.5	25.1	13.5	1.9	41.9	-	2.1	20.88	18	54	28
		15-60	7.0	7.1	12.5	7.9	40.2	716.8	6.3	2,858.4	1.0	497.9	16.0	20.0	0.5	25.0	-	1.9	22.81	16	48	36
2021-22																						
Sub-Humid	Ashland Bottoms	0-15	5.8	6.9	26.7	5.2	54.6	256.0	8.2	1200.3	0.5	157.5	9.5	22.0	1.0	52.5	11.4	1.7	8.07	38	54	8
		15-60	7.2	7.3	5.6	3.8	31.2	156.0	2.3	1562.7	0.4	113.0	4.1	14.9	0.6	26.3	2.5	0.8	9.22	35	53	12
	Belleville	0-15	5.1	6.0	17.5	5.2	75.5	571.9	6.8	1651.2	1.5	224.8	36.9	22.5	1.3	155.7	4.5	2.7	25.32	20	56	24
		15-60	6.0	6.4	8.6	5.0	57.1	730.0	5.4	2732.8	1.6	411.7	19.8	32.4	0.7	121.3	5.1	2.8	28.19	10	54	36
	Great Bend	0-15	5.7	6.4	21.9	4.8	164.1	618.9	8.6	1760.9	1.7	420.4	21.7	57.8	2.3	135.5	7.2	1.9	23.87	20	54	26
		15-60	7.2	7.0	12.9	5.9	57.0	557.9	9.4	3529.9	1.2	910.3	9.1	237.6	0.7	57.2	8.4	1.3	27.70	20	40	40
	Hutchinson	0-15	5.6	6.4	34.5	7.0	84.6	434.7	8.0	2194.9	1.2	386.8	22.3	18.7	0.7	89.7	4.0	3.3	25.11	34	38	28
		15-60	5.9	6.5	21.2	6.0	51.6	386.0	6.4	2650.2	1.1	480.5	14.7	30.7	0.6	87.3	3.2	2.3	26.73	26	44	30
	Manhattan (1 & 2)	0-15	6.6	6.8	10.4	8.0	23.1	243.2	3.5	3459.3	1.1	342.0	17.7	34.1	0.9	55.6	4.1	2.3	26.31	22	50	28
		15-60	7.2	7.0	7.5	7.6	13.4	260.3	4.0	4782.6	1.2	362.3	12.9	113.7	0.6	48.5	3.2	3.0	28.09	22	46	32
	Solomon	0-15	7.1	7.0	22.3	5.7	62.2	263.0	4.9	3415.0	0.9	392.3	11.3	31.8	2.2	48.9	6.3	4.5	21.16	40	36	24
		15-60	7.2	7.0	9.8	7.3	18.5	325.5	4.5	3251.6	0.9	715.6	12.3	66.5	0.8	35.0	7.4	2.5	23.35	20	41	39
Semi-Arid	Belleville	0-15	4.9	5.9	41.8	7.7	56.5	409.0	8.1	2180.3	1.4	372.9	48.1	28.6	0.8	96.9	6.9	2.7	30.39	16	52	32
		15-60	6.1	6.6	25.1	9.3	15.8	484.8	5.4	3887.5	1.2	630.6	19.5	63.7	0.4	58.0	6.6	2.3	33.93	18	42	40
	Garden City	0-15	6.9	7.1	10.5	5.7	39.3	653.0	29.3	1909.1	0.9	510.7	16.4	19.7	0.5	13.1	3.1	1.7	15.56	26	46	28
		15-60	7.9	7.5	10.0	30.1	21.0	550.3	5.5	5221.3	1.0	669.7	9.8	25.7	0.3	9.7	3.9	1.0	33.21	14	56	30
	Hays	0-15	6.0	6.6	26.4	5.2	76.4	709.3	5.7	2369.5	1.3	469.0	20.6	28.4	0.6	45.4	4.1	1.8	25.10	18	52	30
		15-60	6.4	6.8	18.7	4.8	45.5	614.2	4.7	3138.4	1.2	575.3	13.7	32.5	0.4	35.1	3.3	2.0	28.02	22	42	36
	Leoti	0-15	6.8	6.9	28.8	6.0	74.7	692.3	6.8	2767.9	1.1	390.3	20.1	33.4	1.0	42.0	5.8	1.7	19.01	26	46	28
		15-60	7.4	7.2	20.9	5.5	32.7	677.3	6.1	4048.7	1.0	499.6	8.0	37.6	0.6	25.2	5.0	1.8	26.31	26	43	31
*Soil test data were not collected for Tipton, Colbv. or Norcatuar																						

*Soil test data were not collected for Tipton, Colby, or Norcatur

Table B.2. Environmental conditions and soil information for each plot location.

Year	Region	Location	Latitude	Longitude	Altitude	Soil Type	In-season Rainfall (mm)
2020-21	Sub-Humid	Ashland Bottoms (1)	39.14°N	96.63°W	314 m	Belvue silt loam	858
		Ashland Bottoms (2)	39.13°N	96.62°W	313 m	Bismarckgrove-Kimo complex	899
		Belleville	39.82°N	97.67°W	470 m	Crete silt loam	553
		Hutchinson	37.92°N	98.03°W	470 m	Ost Loam	801
		Manhattan	39.22°N	96.59°W	319 m	Kahola silt loam	943
		Tipton	39.30°N	98.26°W	466 m	Harney silt loam	775
	Semi-Arid	Colby	39.39°N	101.06°W	964 m	Keith silt loam	749
		Garden City	37.99°N	100.81°W	879 m	Ulysses silt loam	592
		Leoti	38.29°N	101.20°W	974 m	Richfield silt loam	626
		Norcatour	39.98°N	100.31°W	779 m	Holdrege silt loam	550
2021-22	Sub-Humid	Ashland Bottoms	39.14°N	96.63°W	314 m	Belvue silt loam	1115
		Belleville	39.82°N	97.67°W	470 m	Crete silt loam	761
		Hutchinson	37.96°N	98.12°W	497 m	Funmar-Taver loams	666
		Manhattan (1)	39.22°N	96.59°W	319 m	Kahola silt loam	1138
		Manhattan (2) Late Planted	39.22°N	96.59°W	319 m	Kahola silt loam	1090
		Great Bend	38.36°N	98.87°W	575 m	Taver loam	506
		Solomon	38.88°N	97.35°W	354 m	Detroit silty clay loam	743
	Semi-Arid	Belleville	39.82°N	97.67°W	470 m	Crete silt loam	761
		Colby	39.39°N	101.06°W	964 m	Keith silt loam	275
		Garden City	37.99°N	100.81°W	879 m	Satanta silt loam	293
		Hays	38.85°N	99.34°W	616 m	Harney silt loam	427
		Leoti	38.29°N	101.20°W	974 m	Richfield silt loam	316
		Norcatour	39.98°N	100.31°W	779 m	Holdrege silt loam	296

Table B.3. Energy and Greenhouse Gas Emission coefficients of wheat production inputs and wheat processing inputs used in the Life Cycle Assessment.

Input	Energy (MJ kg⁻¹)	GHG emissions (kg-CO₂e kg⁻¹)	Reference
N Fertilizer	36.41	2.59	Ecoinvent 3.0
N Fertilizer N ₂ O		5.19	IPCC
P Fertilizer	33.25	3.00	Ecoinvent 3.0
K Fertilizer	3.55	0.21	Ecoinvent 3.0
S Fertilizer	16.5	0.793	Ecoinvent 3.0
Wheat Seed	5.57	0.4333	West and Marland, 2002
Herbicide			
Thifensulfuron methyl	179.44	13.48	Ecoinvent 3.0
Tribenuron methyl	179.44	13.48	Ecoinvent 3.0
Metsulfuron methyl	179.44	13.48	Ecoinvent 3.0
Chlorsulfuron	179.44	13.48	Ecoinvent 3.0
Dicamba	179.44	13.48	Ecoinvent 3.0
Glyphosate	148.81	11.19	Ecoinvent 3.0
Fungicide	288.88		West and Marland, 2002
Mefenoxam		9.171	Ecoinvent 3.0
Difenoconazole		9.171	Ecoinvent 3.0
Fluxapyroxad		9.171	Ecoinvent 3.0
Propiconazole		9.171	Ecoinvent 3.0
Pyraclostrobin		9.171	Ecoinvent 3.0
Insecticide	284.82		West and Marland, 2002
Thiamethoxam		9.978	Ecoinvent 3.0

Table B.4. Energy and greenhouse gas emission coefficients of fuel and energy inputs associated with bread production and transportation used in calculations for the current study.

Fuel	Energy (MJ unit⁻¹)	GHG emissions (kg-CO₂e unit⁻¹)	Reference
Diesel			
Manufacture	1.3 MJ ⁻¹	2.69 L ⁻¹	Ecoinvent 3.0
Combustion	38.5 L ⁻¹	2.79 L ⁻¹	EPA, 2023
Natural Gas			
Manufacture	1.13 MJ ⁻¹	0.0098 MJ ⁻¹	Ecoinvent 3.0
Combustion	38.2 m ⁻³	53.11 mmBTU ⁻¹	EPA, 2023
Electricity			
Manufacture	4.1 kWh ⁻¹	5.12 kWh ⁻¹	Ecoinvent 3.0
Use	3.6 kWh ⁻¹	453.6 MWh ⁻¹	EPA, 2023
Gasoline			
Manufacture	1.4 MJ ⁻¹	2.35 L ⁻¹	Ecoinvent 3.0
Use	34.84 L ⁻¹	0.507 km ⁻¹	EPA, 2023

Table B.5. Energy and greenhouse gas emissions and distance assumptions associated with wheat and wheat product transportation.

Method	Energy (MJ unit⁻¹)	GHG Emissions (kg-CO₂e unit⁻¹)	Reference
Truck	1.659 Mg ⁻¹ km ⁻¹	0.117 Mg ⁻¹ km ⁻¹	EPA, 2023
Rail	0.215 Mg ⁻¹ km ⁻¹	0.015 Mg ⁻¹ km ⁻¹	EPA, 2023
Car	2.921 km ⁻¹	0.314 km ⁻¹	
Distance Assumptions			
Destination	Distance (km)	Method	Reference
Elevator	32.18	Truck	Custom Rates 2022
Mill	240	Truck and Rail Average	Anderson et al., 2014
Bakery	2000	Truck and Rail Average	Meisterling et al., 2009
Home	5.52	Car	Bandekar et al., 2022

Table B.6. Diesel quantities by agricultural operation derived from Ibendahl et al, 2021, 2022 (Liters per application per hectare).

Operation	SW KS 2021	NW KS 2021	SC KS 2021	NC KS 2021	SW KS 2022	NW KS 2022	SC KS 2022	NC KS 2022
Fertilizer application	3.83	3.83	3.83	3.83	1.96	1.96	1.96	1.96
Harvest	15.99	15.99	15.99	15.99	13.28	13.28	13.28	13.28
Hauling (Grain cart)	9.35	9.35	9.35	9.35	7.76	7.76	7.76	7.76
Planting	8.04	8.04	7.76	8.04	7.11	7.11	5.80	7.11
Spraying	2.29	2.29	2.29	2.29	1.54	1.54	1.54	1.54

Table B.7. Energy coefficients for flour and bread processing and distribution derived from Avlani and Chancellor, 1977.

Process	Refined Petroleum (1000BTU unit ⁻¹)	Electricity (1000BTU unit ⁻¹)	Natural Gas (1000BTU unit ⁻¹)
Intermediate storage and handling	14.64 Mg grain ⁻¹	8.49 Mg grain ⁻¹	10.55 Mg grain ⁻¹
Elevators and warehousing	13.36 Mg grain ⁻¹	14.40 Mg grain ⁻¹	67.82 Mg grain ⁻¹
Milling	42.08 Mg grain ⁻¹	241.63 Mg grain ⁻¹	26.16 Mg grain ⁻¹
Baking- Large Bakery	417.37 Mg flour ⁻¹	1400.88 Mg flour ⁻¹	4242.29 Mg flour ⁻¹
Distribution	684.74 Mg bread ⁻¹	3.41 Mg bread ⁻¹	15.81 Mg bread ⁻¹
Retailing	278.02 Mg bread ⁻¹	65.75 Mg bread ⁻¹	219.03 Mg bread ⁻¹

Table B.8. Values used to calculate allocation for home transport similar to Bandekar et al., 2022.

Per capita availability of wheat flour ¹ (lbs/year)	Flour makeup in bread by end weight ² (%)	Household spending on bread ³ (\$/lb)	Average household size ⁴ (people)	Annual Food Expenditure per Household ⁵ (\$)	Allocation used ⁶ (%)
82.8	65.1	1.523	2.51	7252.30	2.67
¹ Obtained from the USDA Loss Adjusted Food Availability database for White and Whole Wheat Flour (USDA ERS, 2021) ² Obtained using experiment recipe as an average of all ending bread weight ³ Estimated using consumer price index of bread (U.S. Bureau of Labor Statistics, 2021) ⁴ U.S. Census Bureau, 2021 ⁵ Estimated from total annual household food expenditures (USDA ERS, 2021) ⁶ Calculated as percent of annual household food expenditure spent on bread					

Table B.9. Energy coefficients for bread ingredients derived from the SR Legacy database in FoodData Central (USDA ARS, 2019).

Product Description	Energy content (kJ/100g)
Wheat flour, white, all-purpose, unenriched	1520
Leavening agents, yeast, baker's, active dry	1360
Sugars, granulated	1620
Salt, table	0
Shortening, vegetable, household, composite	3700

Table B.10. Mean GHG emissions and energy inputs adjusted by the functional unit (kg of bread) for the wheat production phase. Means are separated by specific input and by management intensity and are displayed with their respective contribution to wheat production total emissions or energy input (*italics*). Letters denote statistical significance at alpha <0.05 level.

Input	GWP				Energy Input			
	g-CO ₂ e kg-bread ⁻¹				kJ kg-bread ⁻¹			
	% of total				% of total			
	Low	Avg	High	Top	Low	Avg	High	Top
Diesel	64.4 a	55.9 b	55.9 b	56.8 b	467 a	406 b	406 b	413 b
	<i>33.7</i>	<i>20.2</i>	<i>15.6</i>	<i>12.9</i>	<i>38.9</i>	<i>24.1</i>	<i>18.6</i>	<i>15.7</i>
Pesticide	7.3 ab	7.1 b	7.0 b	7.8 a	97 c	95 c	109 b	132 a
	<i>3.3</i>	<i>2.2</i>	<i>1.7</i>	<i>1.5</i>	<i>7.0</i>	<i>4.9</i>	<i>4.5</i>	<i>4.5</i>
Seed	10.3 a	10.1 a	10.4 a	10.0 a	133 a	130 a	133 a	129 a
	<i>5.6</i>	<i>3.8</i>	<i>3.0</i>	<i>2.4</i>	<i>11.4</i>	<i>8.0</i>	<i>6.3</i>	<i>5.1</i>
Sulfur	0.0 d	1.5 c	2.1 b	4.2 a	0 d	31 c	45 b	88 a
	<i>0.0</i>	<i>0.6</i>	<i>0.6</i>	<i>1.0</i>	<i>0.0</i>	<i>1.9</i>	<i>2.1</i>	<i>3.4</i>
Potassium	0.0 b	0.6 a	0.5 a	0.5 a	0 b	10 a	9 a	8 a
	<i>0.0</i>	<i>0.2</i>	<i>0.2</i>	<i>0.1</i>	<i>0.0</i>	<i>0.6</i>	<i>0.4</i>	<i>0.4</i>
Phosphorus	0.0 d	11.1 c	24.5 b	26.4 a	0 d	123 c	271 b	293 a
	<i>0.0</i>	<i>4.2</i>	<i>6.9</i>	<i>6.1</i>	<i>0.0</i>	<i>7.7</i>	<i>12.6</i>	<i>11.3</i>
Nitrogen	35.6 d	62.8 c	85.5 b	111.3 a	500 d	882 c	1202 b	1565 a
	<i>19.1</i>	<i>22.9</i>	<i>23.9</i>	<i>25.3</i>	<i>42.7</i>	<i>52.9</i>	<i>55.5</i>	<i>59.6</i>
N Field	71.4 d	126.0 c	171.7 b	223.4 a	-	-	-	-
Emissions	<i>38.3</i>	<i>45.9</i>	<i>48.1</i>	<i>50.7</i>	-	-	-	-
Total	188 d	275 c	358 b	441 a	1215 d	1704 c	2193 b	2661 a

Table B.11. Mean GHG emissions and energy inputs adjusted by the functional unit (kg of bread) for each phase of the bread production system. Means are separated by phase and by management intensity and are displayed with their respective contribution to wheat production total emissions or energy input (*italics*). Letters denote statistical significance at alpha <0.05 level.

Phase	GHG Emissions				Energy Input			
	kg-CO ₂ e kg-bread ⁻¹				MJ kg-bread ⁻¹			
	% of total				% of total			
	Low	Avg	High	Top	Low	Avg	High	Top
Wheat	0.19 d	0.28 c	0.36 b	0.44 a	1.22 d	1.70 c	2.19 b	2.66 a
Production	<i>15.9</i>	<i>21.5</i>	<i>26.1</i>	<i>30.5</i>	<i>8.1</i>	<i>11.0</i>	<i>13.7</i>	<i>16.3</i>
Milling	0.05 a	0.05 a	0.05 a	0.05 a	2.53 a	2.52 a	2.53 a	2.50 a
	<i>4.0</i>	<i>3.7</i>	<i>3.5</i>	<i>3.3</i>	<i>16.9</i>	<i>16.3</i>	<i>15.9</i>	<i>15.3</i>
Baking	0.542 a	0.540 b	0.540 b	0.537 c	7.16 a	7.13 b	7.13 b	7.09 c
	<i>44.5</i>	<i>41.5</i>	<i>39.0</i>	<i>36.7</i>	<i>47.7</i>	<i>46.1</i>	<i>44.7</i>	<i>43.4</i>
Retail	0.06 a	0.06 a	0.06 a	0.06 a	0.605 a	0.604 a	0.604 a	0.602 a
	<i>5.2</i>	<i>4.9</i>	<i>4.6</i>	<i>4.4</i>	<i>4.0</i>	<i>3.9</i>	<i>3.8</i>	<i>3.7</i>
Transportation	0.370 a	0.369 a	0.369 a	0.368 b	3.51 a	3.50 a	3.50 a	3.49 b
	<i>30.4</i>	<i>28.4</i>	<i>26.7</i>	<i>25.2</i>	<i>23.4</i>	<i>22.6</i>	<i>21.9</i>	<i>21.3</i>
Carbon	0.63 c	0.60 b	0.55 a	0.55 a	-	-	-	-
Sequestration	<i>51.9</i>	<i>46.1</i>	<i>39.9</i>	<i>37.9</i>	-	-	-	-
Bread Output	-	-	-	-	11.80 c	11.76 b	11.76 b	11.69 a
	-	-	-	-	<i>78.6</i>	<i>76.1</i>	<i>73.7</i>	<i>71.5</i>
Total	1.22 d	1.30 c	1.38 b	1.46 a	15.02 d	15.46 c	15.95 b	16.34 a
Net	0.59 d	0.70 c	0.83 b	0.91 a	-3.21 a	-3.70 b	-4.20 c	-4.65 d

Table B.12. Equations of lines for Figure 2.6.

Graph Management Intensity	Equation
Figure 2.6A Bread Yield x GWP	
<i>Low</i>	$y = 1.04x + 1.75x^2 - 7.19x^3$
<i>Average</i>	$y = 1.07x + 2.07x^2 - 7.45x^3$
<i>High</i>	$y = 1.14x + 2.71x^2 - 7.39x^3$
<i>Top</i>	$y = 1.17x + 2.91x^2 - 7.51x^3$
Figure 2.6B Bread Yield x EI	
<i>Low</i>	$y = 13.8x + 115x^2 - 6.04x^3$
<i>Average</i>	$y = 13.9x + 19.3x^2 - 7.41x^3$
<i>High</i>	$y = 14.3x + 23.7x^2 - 7.3x^3$
<i>Top</i>	$y = 14.4x + 23x^2 - 7.54x^3$
Figure 2.6C Bread Yield x Net GWP	
<i>Low</i>	$y = 0.306 + 4.93 \times 10^{-5}x$
<i>Average</i>	$y = 0.567 + 7.88 \times 10^{-6}x$
<i>High</i>	$y = 0.768 - 9.37 \times 10^{-6}x$
<i>Top</i>	$y = 0.987 - 4.03 \times 10^{-5}x$
Figure 2.6D Bread Yield x Net Energy	
<i>Low</i>	$y = -1.45x - 5.52x^2 - 7.58x^3$
<i>Average</i>	$y = -1.41x - 7.09x^2 - 7.85x^3$
<i>High</i>	$y = -2.11x - 11.3x^2 - 7.56x^3$
<i>Top</i>	$y = -2.16x - 11.4x^2 - 7.76x^3$

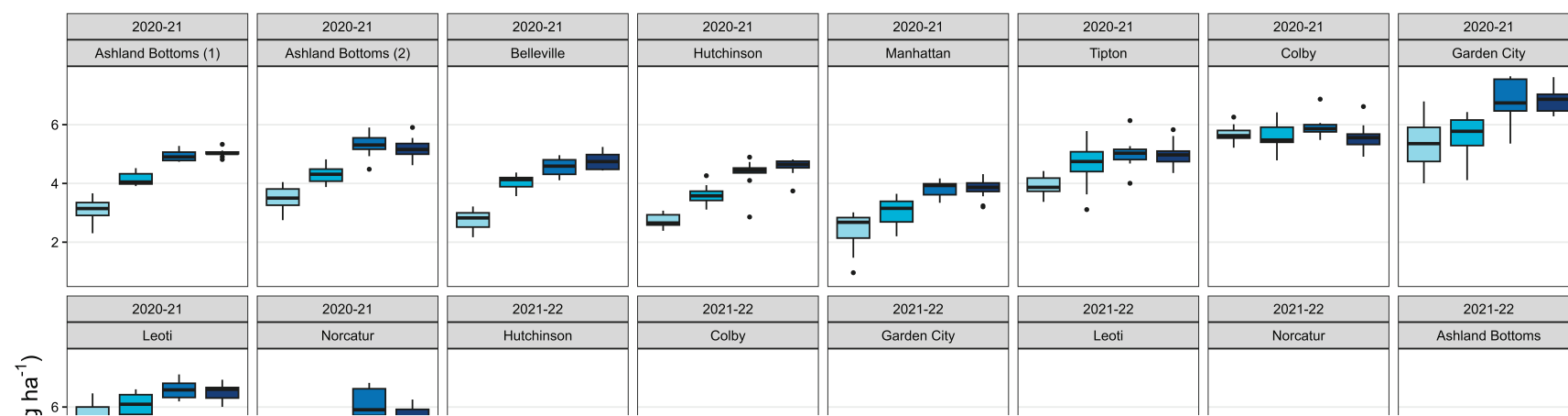


Figure B.1. Grain yield distribution in each experimental study site separated by management intensity.

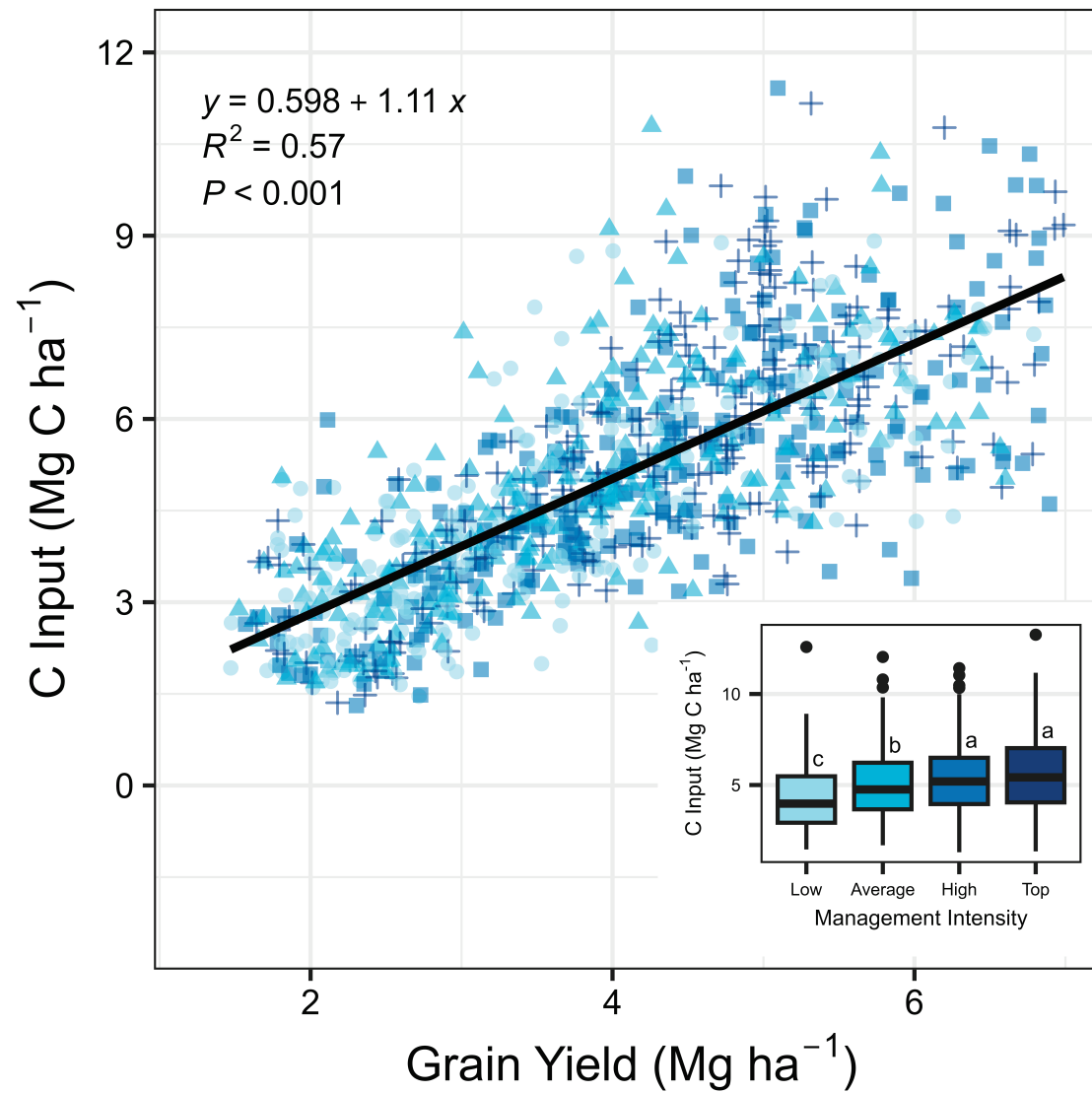


Figure B.2. Carbon inputs to the soil as a function of grain yield. The inset graph displays the distribution of carbon inputs to the soil separated by management intensity. Letters denote statistical differences at the $\alpha < 0.05$ level.

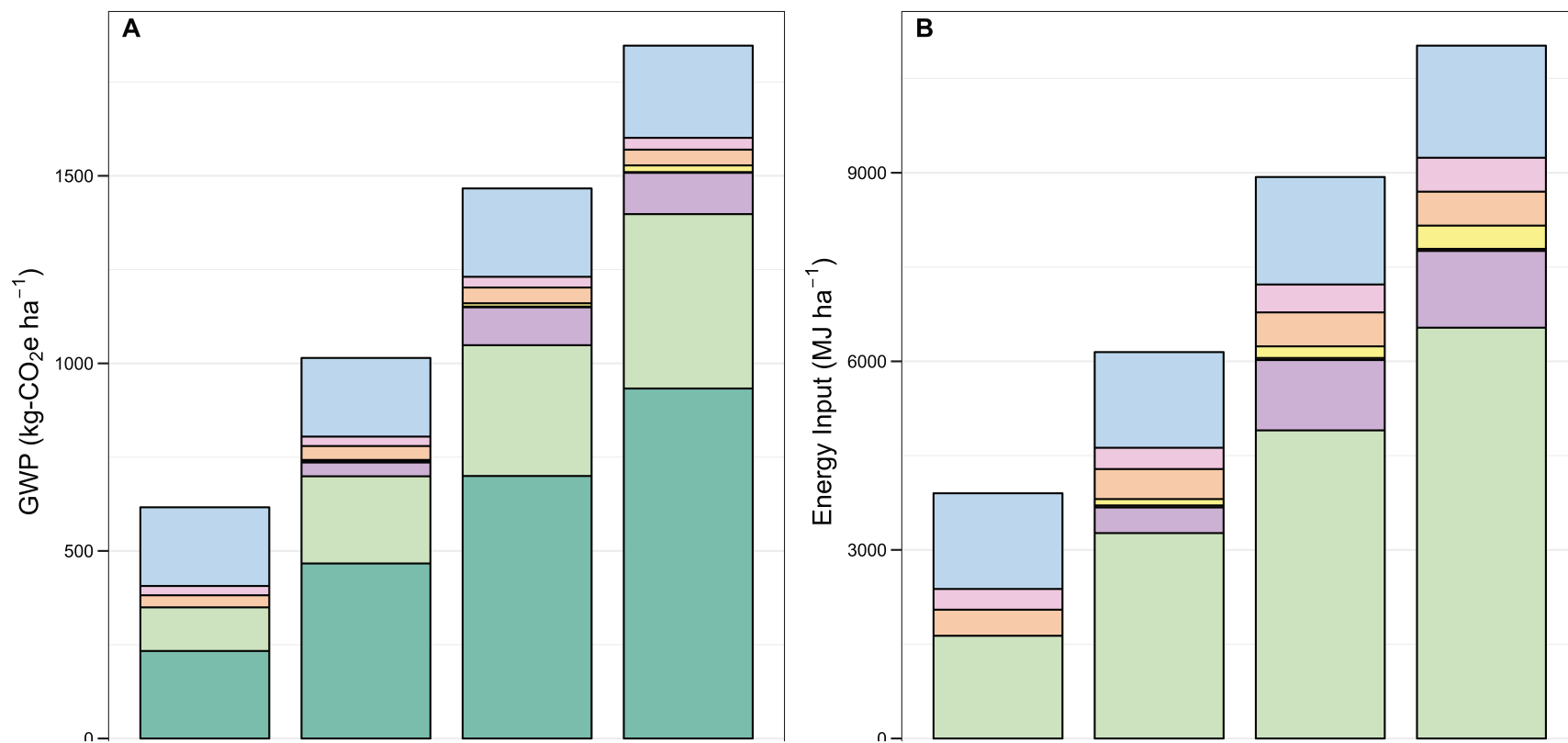


Figure B.3. Contributions of each input of wheat production to (A) global warming potential (GWP) and (B) energy inputs per unit of area and separated by management intensity.

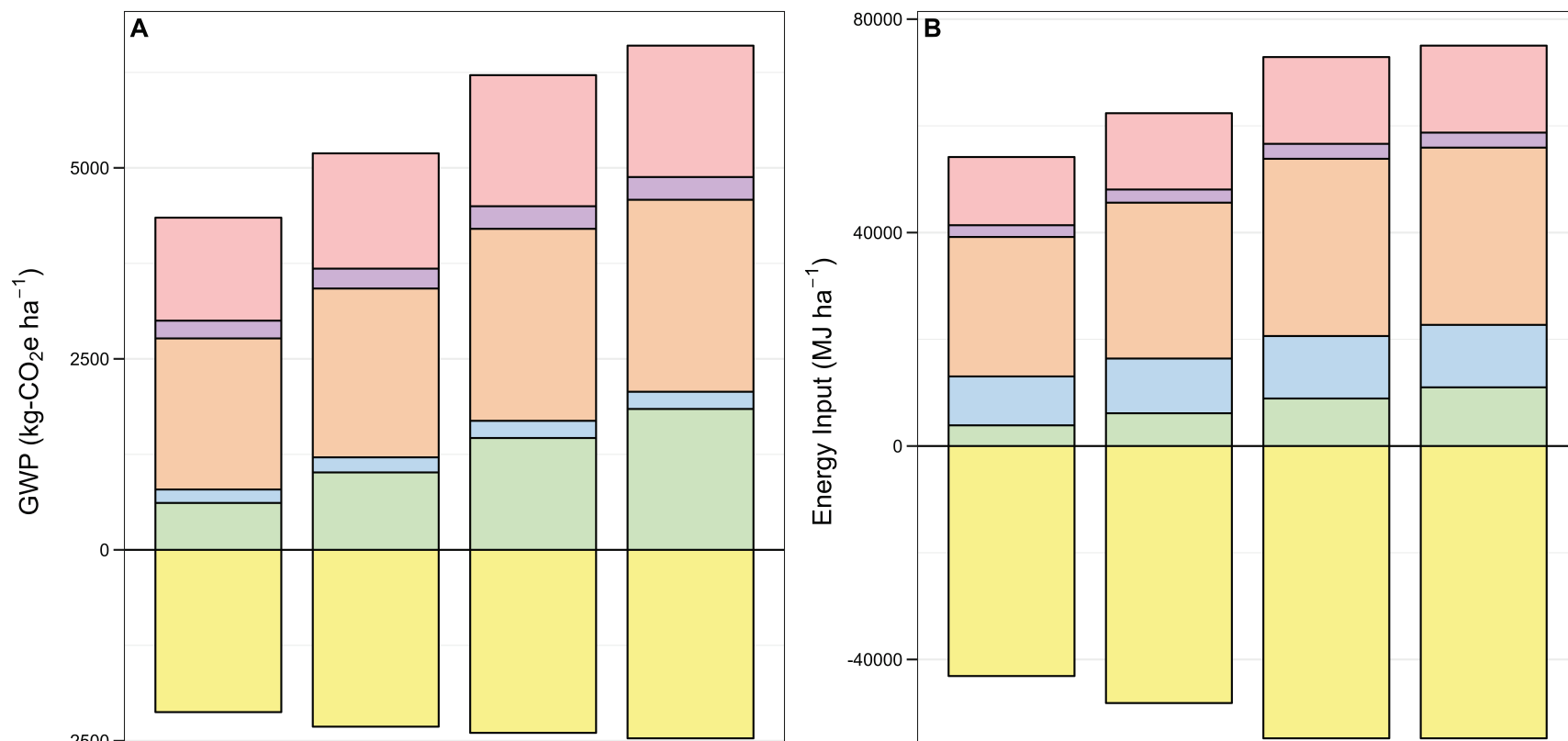


Figure B.4. Contributions of each phase in the bread product system to (A) global warming potential (GWP) and (B) energy inputs per unit of area and separated by management intensity.