ASSESSING THE SUSTAINABILITY OF INTERMEDIATE WHEATGRASS AS A PERENNIAL GRAIN AND FORAGE CROP

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ASSESSING THE SUSTAINABILITY OF INTERMEDIATE WHEATGRASS AS A PERENNIAL GRAIN AND FORAGE CROP

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The sustainability of the global agrifood system is threatened by challenges of providing food security, protecting environmental quality, and mitigating and adapting to climate change. Intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & Dewey], a novel perennial grain crop, hs the potential to improve the environmental sustainability of grain production by improving soil and water quality while also producing grain and forage biomass. Due to lower grain yields than annual grain crops, however, the economic viability of IWG cropping systems is currently uncertain. This dissertation reports the results of research projects that examining IWG cropping systems in central New York, USA, with the goal of identifying factors impacting the agronomic, environmental, and economic potential of these systems.

Chapter 1 focuses on the agronomic productivity and weed community structure of IWG grown in monoculture and intercropped with red clover (*Trifolium pratense* L.) over three years, with organic winter wheat (*Triticum aestivum* L.) used as a comparable annual grain crop. Grain yield of IWG declined over time and was significantly lower than grain yield of wheat in all years. Weed communities of IWG were dominated by perennial grass weeds by the second year. Intercropping red clover increased forage biomass productivity and reduced weed biomass without impacting grain yield of either crop. In Chapter 2, crop productivity and management data from the IWG and wheat systems were used to perform a multi-criteria assessment of the

environmental and economic sustainability. This assessment shows that current IWG grain yields would require substantial price premiums to compete economically with wheat, and that the method of allocating energy usage and GHG emissions to crop products influences how these indicators of environmental sustainability are interpreted. Chapter 3 provides evidence that declines in IWG grain yield are caused by intraspecific competition as crop stand density increases, and that this decline can be mitigated via strip-tillage disturbance after grain harvest. These combined results show that IWG cropping systems have potential to contribute to agricultural sustainability in the northeastern United States, particularly if used for dual-purpose grain and forage production and integrated with high-value livestock and dairy production in the region.

BIOGRAPHICAL SKETCH

Eugene Philip Law is an agroecologist and educator whose research broadly spans the fields of plant ecology, agronomy, crop science, applied economics, and systems dynamics. His academic pursuits are focused on improving the environmental, economic, and social sustainability of agricultural and food systems through collaborative partnerships with other scientists, farmers, food and agriculture industry, and other stakeholder groups. He is also particularly passionate about increasing access and inclusion in agricultural and environmental sciences specifically, and at all levels of STEM education more broadly.

Eugene was born and raised in Syracuse, New York, where he graduated from Bishop Ludden High School in 2008. He then attended the State University of New York College of Environmental Science and Forestry, also in Syracuse, New York, from 2008 to 2016, earning a B.S. in environmental resources engineering and environmental biology and a M.S. in environmental science and ecosystem restoration in that time. Outside of his education, he has worked as a janitor, grocery clerk, lifeguard, commercial printer, police dispatcher, educational outreach specialist, and elementary school teacher. His research has been published in the Journal of Cleaner Production, Renewable Agriculture and Food Systems, CourseSource, Ecological Engineering, and Restoration Ecology.

Eugene will soon be starting a postdoctoral fellowship with the USDA Sustainable Agricultural Systems Lab in Beltsville, Maryland, where he will be working with the Getting Rid of Weeds (GROW) integrated weed management program to analyze data and communicate findings from a XX-institution research network that was developed to improve the sustainability of weed management practices and combat the herbicide resistance epidemic.

In memory of Michael Harmon and Richard Romeo.

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Table 10. Sensitivity analysis of the effect of Kernza grain and forage yields on Kernza grain price required to match returns from an organic corn-soybean-spelt rotation. Kernza yields are based on low and high values observed in field trials in New York and other published studies.

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PROLOGUE

Global challenges to agricultural sustainability

One of the greatest challenges of the 21st century is transforming the global agri-food system to meet food security needs of a growing human population, providing farmers, agriculture and food workers, and other stakeholders with fair and equitable livelihoods, all while adapting to climate change and protecting the natural capital that sustains agroecosystems (Bailey and Buck, 2016; Foley et al., 2011). Feeding a global human population projected to reach 9.7 billion by 2050 and more than 11 billion by 2100 will require increasing the efficiency of food production and distribution, including reducing food waste and encouraging more sustainable diets (Gerten et al., 2020; Springmann et al., 2018; United Nations Department of Economic and Social Affairs, 2017). Agriculture is among the leading sources of environmental degradation, including water (Evans et al., 2019) and air pollution (Carlson et al., 2017), soil erosion (Xiong et al., 2019), and loss of biodiversity and native habitat (Dudley and Alexander, 2017). In particular, the contribution of agriculture to global greenhouse gas (GHG) emissions through land use change and crop and livestock production has exacerbated climate change (Carlson et al., 2017). At the same time that it creates negative environmental impacts, agricultural production is threatened by soil loss and degradation (Gomiero, 2016), increasing water scarcity (Varis et al., 2017), increased biotic stress due to pesticide resistant weeds, insects, and diseases (Jørgensen et al., 2018) that are frequently expanding in range (Miedaner and Juroszek, 2021), and climate change (Campbell et al., 2017).

Climate change is expected to greatly impact agricultural land use through shifts in where and how much of certain crops are grown, and the intensity of crop production and management that is possible (Iizumi and Ramankutty, 2015). The prospect of increasing the amount of land used for agriculture is unlikely to increase production efficiency, as the most productive arable lands are already at nearly full utilization (Lambin and Meyfroidt, 2011). Expansion of agriculture into new areas will result in encroachment on lands that are increasingly less productive per unit area and per unit of labor and material inputs (Smith, 2013; Spiertz, 2012), that are more vulnerable to degradation and non-point source pollution (Cassman et al., 2003), and that are currently supporting ecosystems that provide important services such as wildlife habitat, water purification, carbon storage, and nutrient cycling that are not available from large-scale monocultures of commodity crops (Asbjornsen et al., 2014; Tscharntke et al., 2012). On the other hand, increasing the production of current agricultural land will be increasingly difficult as in some parts of the world yields of many crops are approaching theoretical maximums (Cassman et al., 2003; Fischer and Edmeades, 2010; Neumann et al., 2010), and because much of the advancement in annual crop yields over the 20th century has relied on energy subsidies in the form of fuel and agrochemicals for fertilization and pest management that are not sustainable indefinitely (De Laurentiis et al., 2016; Hoff, 2011) and produce environmental externalities such as soil loss and water and air pollution (Crews et al., 2018).

Increasing total crop yields is not the only way to address food security issues, however, and efforts that focus solely on crop yield may exacerbate environmental degradation (Hunter et al., 2017). It is estimated that less than half of harvested, edible crop biomass is consumed as food, so reducing losses in production and processing and changing consumer behavior to reduce food waste and eat diets with fewer animal products and less over-consumption can have a large impact on food security (Alexander et al., 2017; Poore and Nemecek, 2018; West et al., 2014). Developing cropping systems that produce fewer GHG emissions and prevent soil erosion and nutrient losses that impair water quality has also been identified as a key to mitigating climate change and achieving long-term agrifood system sustainability, but is often overlooked in the discourse around food security (Hunter et al., 2017; West et al., 2014). When analysis of cropping systems is expanded to the landscape scale, tradeoffs between crop yields, ecosystem services, and environmental quality can be managed by diversifying crops and their management in space and time, with some agricultural land uses emphasizing services other than high yields (van Oosterzee et al., 2014). Addressing these challenges of producing adequate food, fodder, and fiber within the shrinking constraints of water scarcity, rural poverty, and global climate change will define the future of agronomy and agroecology (Hoff, 2011).

Ecological intensification of agriculture

In pursuing solutions to the challenge of maintaining or increasing agricultural production without expanding the area farmed on vulnerable or unsuitable land or relying on unsustainable external inputs many frameworks have been proposed for the ecological or sustainable intensification of agriculture (Rockström et al., 2017; Tittonell, 2014). Definitions of ecological and sustainable intensification vary (Smith, 2013; UN FAO Committee on Agriculture, 2010; Wezel et al., 2015), but typically involve increasing food production without sacrificing future potential to produce food through further degradation of natural capital, by replacing a some or all of the material inputs utilized in conventional agriculture with natural functions of agroecosystems, i.e. ecosystem services. Specifically, the definition of ecological intensification that has informed the research in this dissertation comes from Bommarco et al. (2013):

> "Ecological intensification entails the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices. Effective ecological intensification requires an understanding of the relations between land use at different scales and the community composition of ecosystem service-providing organisms above and below ground, and the flow, stability, contribution to yield, and management costs of the multiple services delivered by these organisms."

Restoring ecosystem services to agricultural land through targeted management that harnesses and enhances ecosystem functions rather than replacing them with external inputs will be a key step in developing more sustainable cropping systems (Foley et al., 2005).

The ecosystem services most relevant to agricultural productivity and sustainability include nutrient cycling, soil formation and retention, natural pest suppression, water storage and filtration, pollination, natural genetic variation, and atmospheric regulation (Zhang et al., 2007). Many also recognize that ecological intensification cannot solely focus on environmental concerns and must incorporate economic and social sustainability of agricultural and food systems into research and development, and as a result will likely require governmental support through regulation, enforcement, and incentivization of behaviors (Phalan et al., 2016). It is necessary that these intensification efforts emphasize agroecosystems that produce grain crops, as grains are grown on approximately 70% of global cropland and provide over 60% of human calories and thus represent one of the largest areas for improvement in both productivity and sustainability (Pimentel et al., 2012).

Opportunities of perennial grains

One prospect for ecological intensification of grain cropping systems is the development of perennial grain crops. Perennial grain crops that are planted once and then harvested for several years would be expected to have numerous environmental benefits including soil conservation, soil health improvement, water quality improvement, and improved wildlife habitat, in addition to the inherent reduction in fuel, labor, machinery, and other inputs compared to annual grain production (Asbjornsen et al., 2014; Crews et al., 2018; Pimentel et al., 2012). Incorporating perennial grain crops into agricultural landscapes fits neatly into the aspect of the water-energy-food security nexus that Hoff (2011) describes as "benefiting from productive ecosystems", in which agroecosystems would be redesigned to build, rather than extracting, natural capital.

History of Kernza intermediate wheatgrass, the first perennial grain

Historically perennial grasses were harvested for their edible seed by many cultures around the globe, some of which even cultivated perennial grasses for centuries. In North America indigenous peoples gathered seeds of at least a dozen different grass species including wild rice (*Zizania* spp.), Norse settlers of Iceland and Greenland cultivated wildrye (*Leymus arenarius*), and farmers in the Southern Caucasus cultivated perennial relatives of wheat and rye including mountain rye (*Secale montanum*) until as recently as the early 1900s (Wagoner, 1990a). In each of these cases, however, annual species were quickly adopted for the vast majority of grain production when they became available due to their higher productivity and other management considerations.

The first major efforts to develop perennial grain crops started in the 1920s in the Soviet Union where hybridization of wheat with wild perennial relatives to introgress perennial genes was pursued for several decades (Wagoner, 1990a). Difficulties in achieving hybrid wheat varieties that were perennial, high-yielding, and didn't exhibit other problematic traits such as high levels of winter-kill and lodging caused these breeding programs to shift their focus towards improving annual wheat rather than developing perennial crops by the 1960s (Menadbe and Eritsyan, 1962). Interest in developing perennial grasses for agricultural uses was also high in Western Europe and North America in the same time period (1920s-1960s) but focused primarily on forage rather than grain production (Wagoner, 1990a). Some breeding of perennial wheat varieties via hybridization was attempted at UC Davis in the 1940s but never achieved economic yields and was abandoned (Suneson and Pope, 1946).

In the 1970s and early 1980s the founding of The Land Institute and Wes Jackson's book "New Roots for Agriculture" (1985) caused some increased activity in breeding perennial hybrids or identifying wild perennials to domesticate as grain and oilseed crops. It was around this time that the development of intermediate wheatgrass as a perennial grain crop began in Kutztown, Pennsylvania at the Rodale Institute. At Rodale, Dr. Peggy Wagoner screened nearly 100 species of wild perennial grasses for domestication potential based on vigor, seed size, threshability, synchronous maturity, low shattering and lodging, suitability for mechanical harvest (i.e. consistent height), and food quality characteristics (Wagoner, 1990b). From this screening intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & Dewey] was selected as the most promising candidate for domestication. A breeding program was then started utilizing 250 accessions of IWG, many previously developed for forage production and others collected from the species' native range in the Soviet Union, Iran, and Turkey (Wagoner, 1990b). From there improved germplasm was transferred to the USDA Soil Conservation Service Plant Materials Center in Big Flats, New York in 1990, and then to The Land Institute, Salina, Kansas in 2001 where a breeding program was developed by Dr. Lee DeHaan (DeHaan et al., 2018). Continued breeding at The Land Institute, the University of Minnesota, and other partner institutions eventually led to the development of Kernza®, a trademarked brand of perennial grain from specific IWG varieties (Bajgain et al., 2020). Demand for Kernza grain has led to IWG becoming the perennial grain crop that is perhaps the closest to widespread adoption and commercial viability in the United States (Muckey, 2019).

Research on IWG currently spans a wide array of disciplines including plant breeding and genetics, agronomy, soil science, biogeochemistry, food science, and agricultural and consumer economics. Recent publications have reported on the IWG genome and its use in accelerating the progress of breeding programs (Crain et al., 2021; Kantarski et al., 2017), physiology and phenology (Duchene et al., 2021; Jungers et al., 2018), agronomic management and productivity (Fernandez et al., 2020; Hunter et al., 2020a), and the biogeochemistry of intermediate wheatgrass stands (de Oliveira et al., 2020; Sprunger et al., 2019), food science applications (Marti et al., 2019; Tyl et al., 2020; Zhong et al., 2019), farm budgets for IWG production (Hunter et al., 2020b), and consumer willingness to pay for food products made with IWG grain (Homami, 2020). An integrative study of the agronomic, environmental, and economic impacts perennial IWG grain cropping systems in comparison to annual grains has not yet been attempted to our knowledge.

Dissertation overview

This dissertation attempts to provide a holistic evaluation of IWG cropping systems grown for grain and forage production in New York State. In Chapters 1 and 2, I conduct a systems comparison of IWG and annual winter wheat (*Triticum aestivum* L.), a small grain crop that is frequently grown by organic farmers in New York state. These two chapters are based on data collected from a three-year field experiment where IWG and wheat were each grown in monoculture and intercropped with medium red clover (*Trifolium pratense* L.). Medium red clover is a perennial forage legume that complements cereal crops by fixing atmospheric nitrogen, suppressing weeds, and moderating soil microclimate (Gaudin et al., 2013). Chapter 1 focuses on the agronomy of IWG as a perennial grain and forage crop. Grain yield and components of yield are emphasized due to the demand for Kernza grain, but the higher forage production of the IWG-red clover polyculture presents opportunities for dual-use production of grain and forage that could balance the economic challenges of lower grain yields from IWG. Chapter 1 also examines how weed community structure develops in IWG cropping systems over time.

Chapter 2 expands on the agronomic focus of Chapter 1 to more closely examine the economic and environmental impact of organic IWG cropping systems. For these analyses, IWG is compared to the annual wheat systems described in

Chapter 1 and a corn-soybean-spelt system that is typical of organic grain farming in upstate New York. Changes in soil health indicators over the three years of the field experiment are reported, enterprise budgets and sensitivity analyses are used to estimate prices for Kernza grain, energy consumption and greenhouse gas emissions during crop production are estimated using the Farm Energy Analysis Tool (FEAT; Camargo et al., 2013), and the overall environmental impact and relative reliance on renewable versus purchased inputs are assessed using the emergy method (Odum, 1996).

Chapter 3 changes the focus from understanding the potential benefits and drawbacks of IWG production relative to annual small grains to testing strategies for managing IWG stands as they age. Decline in IWG grain yield over time has been well documented including in the field experiment described in Chapters 1 and 2. Based on observations from multiple field trials, I hypothesized that vigorous vegetative reproduction was increasing IWG stand density from year to year, thereby causing intraspecific competition for light, water, nutrients, and space that could decrease seed production. Chapter 3 describes the results of using strip-tillage to thin a three-year-old IWG stand at two times in the crop's annual reproductive cycle: in late fall after post-harvest regrowth has occurred, and early the following spring after plants have left winter dormancy but before reproductive tillers have fully developed.

The experiment described in Chapters 1 and 2 represents the first research on organic IWG grain and forage production in the Northeastern United States, and is the first use of FEAT and emergy methods to evaluate the sustainability of a perennial grain crop. The strip-tillage intervention described in Chapter 3 provides preliminary evidence for an effective IWG crop management strategy to address the problem of low grain yields. The epilogue reflects on these projects and provides some ideas for future directions of research in IWG and other perennial grain cropping systems.

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CHAPTER 1

INTERCROPPING RED CLOVER WITH INTERMEDIATE WHEATGRASS SUPPRESSES WEEDS WITHOUT REDUCING GRAIN YIELD

1.1 Abstract

Intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & Dewey] is the first commercially produced perennial grain crop in the United States. Intercropping legumes with IWG has the potential to enhance dual-purpose grain and forage production and contribute to weed control in organic management systems. We compared IWG to annual winter wheat (*Triticum aestivum* L.) in monoculture and intercropped with red clover (*Trifolium pratense* L.) in a three-year experiment in central New York, USA. Grain yield of IWG was lower than wheat in all years, partly due to lower tiller fertility and seed size in IWG. Compared to grain yield of 1212 kg ha^{-1} in the first year, IWG grain yield was 83% lower (202 kg ha^{-1}) and 64% lower (441 kg ha^{-1}) in the second and third years, respectively. IWG straw production increased 40% from 5541 kg ha^{-1} to 7785 kg ha^{-1} over three years while wheat straw yield declined from 5167 to 3533 kg ha^{-1}. Red clover did not affect grain or straw yield of either crop but did reduce weed biomass and weed species richness. Weed communities in IWG plots were dominated by perennial grasses by the second year of production, whereas annual weeds were dominant in wheat throughout the experiment. Preventing establishment of perennial weeds that will persist in perennial grain cropping systems should be a management priority. High forage production observed when comparing IWG and wheat suggest opportunities for including IWG in

integrated crop-livestock systems where IWG's higher forage yield and quality has higher utility.

1.2 Introduction

Globally, agriculture is facing unprecedented challenges of simultaneously producing enough food to support a growing human population, protecting the natural capital that underpins agroecosystems, and providing farmers and other stakeholders with sustainable livelihoods (Bailey & Buck, 2016; Foley et al., 2011). Annual grain crops comprise upward of 70% of global food production and thus heavily contribute to the challenges to agricultural sustainability outlined above (Pimentel et al., 2012). Perennial grain crops are a potential alternative source of staple foods and animal forages that can also provide additional environmental benefits and potential production efficiencies over annual crops (Glover et al. 2010). Incorporating perennial plants into the agricultural landscape enhances many ecosystem services, including soil and water quality, pest and pathogen control, and resilience to climate change and extreme weather events (Asbjornsen et al., 2014). Fewer tillage and planting operations in perennial systems also reduces fuel and labor inputs, thereby reducing greenhouse gas emissions, and when combined with extensive root systems may result in net carbon storage in perennial cropping systems (Kantar et al., 2016). The extensive root systems of perennial grains may also increase their water and nutrient use efficiencies, potentially reducing the need for fertilizer and irrigation inputs (Kantar et al., 2016). Greater crop diversity, both within perennial polyculture systems at the field level and across the agroecological landscape, contributes to improved habitat for wildlife (Crews et al., 2018).

Intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & Dewey] is a cool-season perennial grass that has been used as a forage species in the United States since the mid-20th century. Kernza is the trademarked brand for the grain harvested from licensed varieties of intermediate wheatgrass bred for grain production by researchers at The Land Institute, Salina, Kansas, USA and partner institutions (Bajgain et al., 2020; DeHaan et al., 2018) that has recently gained interest from growers and the food industry because of its perceived agronomic and environmental benefits (Lanker et al., 2020). Intermediate wheatgrass provides many of the ecosystem services desired from perennial cropping systems, including reduced nitrate leaching compared with annual wheat (Culman et al., 2013) and maize (Jungers et al., 2019) due to its greater whole-crop nitrogen use efficiency (Sprunger et al., 2018) and water use efficiency (de Oliveira et al., 2020). Intermediate wheatgrass also enhances diversity of soil microbial (Duchene et al., 2020) and microinvertebrate communities (Sprunger et al., 2019) compared to annual small grains, and has the potential to be a net carbon sink (de Oliveira et al., 2020) due to its high root biomass production (Pugliese et al., 2019; Sakiroglu et al., 2020).

Intermediate wheatgrass grain yields are currently significantly lower than for annual small grain crops and decline further as stands age (Hunter, Sheaffer, Culman, & Jungers, 2020). A more in-depth understanding of the biology of the crop and the ecology of the cropping system will better inform more targeted management interventions in the future. For example, a better understanding of IWG growth and development will aid in managing this crop for the dual-purpose production of grain and forage (Jungers et al., 2018), a possible economic offset of low grain yields (Ryan et al., 2018). Quantifying components of grain yield such as tiller density, tiller fertility, and seed size can also provide insight into other management challenges, such as the physiological factors causing yield decline over time (Fernandez et al., 2020; Jungers et al., 2018). For example, floret site utilization and reproductive tiller number are primary components of grain yield for spaced plants in IWG breeding programs (Altendorf et al., 2021), but the traits governing yield in the environment of a production stand may differ and will likely be affected by stand age (Cattani, 2017)

Weed management has not been widely studied in perennial grain crops and has the potential to contribute to improved crop productivity (Zimbric et al., 2020). Farmers have identified both organic and conventional weed management as a research priority in the development of perennial grain cropping systems (Lanker et al., 2020; Wayman et al., 2019). Early demand for Kernza perennial grain from food processors has largely focused on organic production (Lanker et al., 2020) due to the environmental sustainability attributes of the crop that appeal to consumers and contribute to corporate sustainability goals. Weeds are the single most limiting management factor in organic annual small grain production (Kolb & Gallandt, 2012), yet options for mechanical weed control (i.e., cultivation) that are becoming more common in organic annual small grains are even more limited in perennial grain crops. Therefore, knowledge of weed community dynamics is even more important in perennial crops to inform the use of other mechanical (e.g., mowing) or cultural (e.g., weed-suppressive intercrops, seeding rate, planting date) weed management practices. Conventional production of IWG grain is anticipated to increase as chemical pesticides become labeled for use in this crop. Identifying problematic weed species will assist in prioritizing target weeds for herbicide trials.

While perennial grain crops present many environmental benefits when grown in monoculture, perennial polycultures have the potential to be even more productive and sustainable (Crews et al., 2018). Interseeding medium red clover (*Trifolium pratense* L.) is a common practice in winter wheat (*Triticum aestivum* L.) due to the clover's ability to fix atmospheric nitrogen, reduce soil erosion, moderate soil temperature and evaporation, and suppress weeds without negatively impacting wheat grain yields due to the complementarity between grasses and legumes in mixture (Bybee-Finley & Ryan, 2018; Gaudin et al., 2013). Frost-seeding, where clover seed is broadcast in early spring into winter cereals planted the previous fall, has been shown to provide excellent weed suppression while minimizing inter-crop competition with organic winter wheat (Koehler-Cole et al., 2017). Intercropping forage legumes such as red clover with perennial cereals has similar potential to enhance the functionality of the overall cropping system with respect to soil health regeneration, soil and water protection, nutrient cycling, forage production, and pest suppression (Ryan et al., 2018). Intercropping medium red clover with IWG has previously been found to increase total forage yield, crude protein content, and relative forage quality compared to monoculture IWG, but substantially decreased grain yield in the first year of production (Favre et al., 2019). Understanding these benefits and drawbacks will allow the development of management practices for successful perennial grain polycultures.

Here we report on the first agronomic assessment of IWG production in the Northeast United States, with hard red winter wheat (*Triticum aestivum* L.) as a comparable annual small grain grown in the region. Medium red clover was also interseeded into both grain crops to determine if the polyculture provided additional benefits. The objectives of this research were to: (1) evaluate the grain and forage productivity of IWG relative to winter wheat with and without red clover over three years, (2) compare trends in components of grain yield, and (3) assess weed community structure and biomass over time.

1.3 Methods

1.3.1 Experimental Design and Management

A field experiment was conducted between 2016 and 2019 at the Cornell Musgrave Research Farm, Aurora, New York, USA (42.7222 N, 76.6636 W) to compare the agronomic productivity, components of grain yield, and weed communities of perennial and annual small grain cropping systems. Soil type at the site is Honeoye silt loam with a pH of 7.5 and 3.2% organic matter. Mean annual temperature was 9.1°C and mean annual precipitation was 918 mm based on the most recent NOAA 30-year climate averages for this site (Arguez et al., 2012). The experiment was set up as a split-plot randomized complete block design with four blocks. Each subplot measured 18.3 m by 3.05 m. Main plot treatments were Kernza intermediate wheatgrass from the third cycle of selection for increased grain yield in The Land Institute's breeding program (DeHaan et al., 2018) and hard red winter wheat (cv 'Warthog'). This field site had previously been used to grow a continuous corn-soybean-wheat rotation, with soybean as the immediate preceding crop, using conventional farming practices including annual tillage and use of synthetic fertilizers and pesticides. Seedbed preparation for the experiment included moldboard plowing followed by disking and cultipacking to create a firm, smooth seedbed. Both grain crops were planted on August 31, 2016 using a John Deere 1590 no-till grain drill (John Deere US, Moline, Illinois, USA) with 19 cm row spacing that is typical for small grains in the Northeast US. The seeding rate for IWG was 16.8 kg ha^{-1} and seeding depth was 1.25 cm, whereas the seeding rate for wheat was 107.6 kg ha^{-1} and seeding depth was 2.5 cm. Split-plot treatments were interseeded medium red clover (*Trifolium pratense* L.) and a no clover control. Red clover seed was frost-seeded in March of 2017 in both IWG and wheat main plots at a high seeding rate of 22.4 kg ha^{-1} that was selected based on advice that in previous attempts IWG had quickly outcompeted red clover seeded at lower rates (S. Culman, personal communication, January 20, 2017).

Field operations included primary and secondary tillage, fertilizer application, planting, harvesting, and post-harvest straw management for all plots (Table 2). A false seedbed was used to manage weeds prior to crop seeding by allowing two weeks for weeds to germinate between primary tillage on August 16 and secondary tillage, fertilization, and seeding operations on August 30 and 31. Soil and crops were managed organically according to the USDA National Organic Program regulations; however, the field was not certified organic. All purchased seed was certified organic, approved fertilizers were utilized, and no prohibited inputs were applied. Composted chicken manure (5-4-3, Kreher Family Farms, Clarence, New York, USA) was broadcast at a rate of 900 kg ha^{-1} in all plots in both fall and spring of each year, with the goal of applying 90 kg N ha^{-1} annually to approximate agronomically optimum N rates for IWG grain production (Jungers et al., 2017). Grain was harvested from all plots with a PMC20 plot combine (Almaco, Nevada, Iowa, USA) immediately after quadrat sampling each year (details below). Post-grain harvest straw management was accomplished by flail chopping and removing all residues above 10 cm in height one to two weeks after grain harvest of each crop. In 2017 and 2018 wheat was re-planted in the same plots in mid-September. Although continuous cropping of winter wheat is not a common practice in New York, this design allowed for a straightforward comparison of IWG and wheat while avoiding any confounding effects of growing wheat in different areas each year. Seedbed preparation for replanting involved moldboard plowing, disk harrowing, and cultipacking prior to seeding at the same rates and depths as in 2016. Red clover was re-seeded in both IWG and wheat plots in March 2018, but was only reseeded in wheat plots in March 2019 due to the vigorous clover growth in IWG plots in 2018. Red clover was removed by hand in early May 2019 where it was encroaching into no-clover IWG plots.

Table 1: Schedule of field operations between 2016 and 2019 in Aurora, New York.

Field Operation	Equipment Utilized	2016	2017	2018	2019
Primary tillage	Moldboard plow	Aug. 16	-	-	-
Fall fertilizer application	Drop spreader	Aug. 30	Sep. 13	Sep. 13	-
Secondary tillage and planting	Disk harrow, cultipacker, grain drill	Aug. 31	Sep. 14	Sep. 14	-
Frost seeding red clover	None (broadcast by hand)	-	Mar. 29	Mar. 22	Mar. 19 [1]
Spring fertilizer application	None (broadcast by hand)	-	Apr. 19	Apr. 20	Apr. 25
Wheat grain & straw harvest	Plot combine, flail chopper	-	July 19	July 11	July 15
Kernza grain & straw harvest	Plot combine, flail chopper	-	Aug. 9	Aug. 15	Aug. 23

[1] Red clover was only frost seeded into wheat plots in 2019

1.3.2 Data Collection

Grain crop, red clover, and weed biomass samples were collected from two 0.5 m^2 quadrats in each subplot at crop maturity, which varied by grain crop. Plot edges were avoided. Within each 76 cm by 66 cm quadrat, which are designed to sample four crop rows at 19 cm spacing, all crop plants and all weeds larger than 2.5 cm in diameter or height were clipped at the soil surface and separated by species. Biomass from the two quadrats per subplot was then combined into a single sample representing 1 m^2 of area for that subplot for each species collected. Crop biomass was further separated into stems and seedheads which were counted to estimate crop stand density and fertile tiller percentage. Biomass samples were dried for at least five days at 65°C before weighing. Twenty mature seedheads from each sample were randomly selected for measurement of components of yield. In 2017 this subsampling occurred in the lab after samples were dried; in 2018 and 2019 subsampling was done while collecting samples in the field in order to avoid seedhead breakage during transport and drying. The yield components measured for the 20 seedhead subsample were seedhead length and weight, floret count, seed count, and seed weight, all of which were measured at harvest and thus are not representative of total reproductive potential due to shattering that occurred before harvest. Remaining seedheads were weighed intact, threshed, and dehulled using a hand deawner/debearder (Hoffman Manufacturing Inc., Corvallis, Oregon, USA), and reweighed as naked seed. All IWG and wheat seed weights and yield estimates were normalized to 13.5% moisture content which is the standard for wheat markets. All straw, red clover, and total forage yields are presented as dry weights. In plots without interseeded red clover, straw yield was equivalent to total forage yield, while in plots with red clover, clover biomass and straw biomass were combined to estimate total forage yield.

1.3.3 Data Analysis

All data analysis was performed in R statistical software version 4.02 (R Core Team, 2020). Linear mixed-effects models were created using the 'lme4' package (Bates et al., 2015) to analyze differences between treatments for grain yield, all components of yield, straw biomass, red clover biomass, total forage yield, weed biomass, and weed species richness and evenness. Crop species, intercrop, and year were treated as fixed effects and block and the main-plot treatment (to account for split-plot randomization) were treated as random effects in these models. Weed species richness and evenness were calculated using the 'specnumber' and 'diversity' functions from the ‘vegan’ package (Oksanen, 2020). Grain yield, total forage yield, weed biomass, and seedhead weight and length data were log-transformed, and fertile tiller percentage data were arcsine transformed, to satisfy assumptions of normally distributed errors and homogeneity of variance. Treatment means reported for these transformed variables represent a back-transformation of estimated marginal means calculated with the ‘emmeans’ package (Lenth, 2020). Post-hoc comparisons of means were conducted using Tukey’s HSD using the ‘emmeans’ package. Weed species rank abundance was calculated using the ‘rankabuncomp’ function from the ‘BiodiversityR’ package (Kindt & Coe, 2005). All tests used $\alpha = 0.05$ as the cutoff for significant effects.

1.4 Results

Annual temperatures tended to be higher than the 30-year average (Arguez et al., 2012) and cumulative precipitation exhibited considerable variation between 2016 and 2019 when the experiment was conducted (Figure 1). Fields were dry and very little rainfall was observed for the first six weeks after crops were planted in 2016 before almost 200 mm fell in a single day in late October 2016. Precipitation was above normal throughout the 2017 growing season. In 2018 there was a prolonged drought between May and mid-July. Both temperature and precipitation were closest to the 30-year averages in 2019.

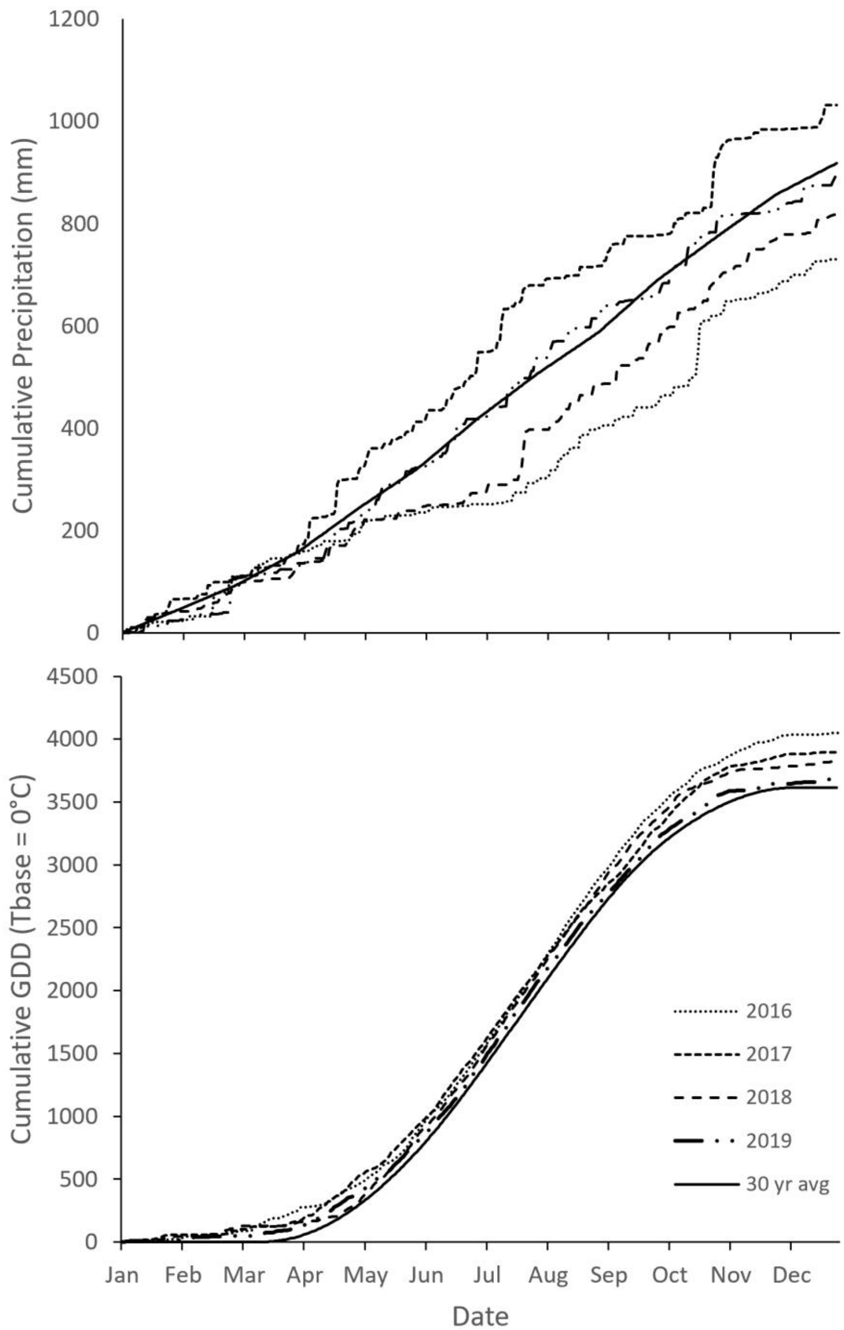

Figure 1: Cumulative precipitation and growing degree days (Tbase = 0°C) for the experimental site between 2016 and 2019. The most recent NOAA 30-yr climate averages (1981-2010) are included for reference.

1.4.1 Grain yields

Averaged over three years, wheat produced 487% more grain than IWG (Table 2). Intermediate wheatgrass grain yield was highest in 2017 at 1212 kg ha^{-1}, dropped to 202 kg ha^{-1} in 2018, then rebounded slightly to 441 kg ha^{-1} in 2019. In contrast, wheat grain yields were 3429 kg ha^{-1} in 2017, 2644 kg ha^{-1} in 2018, and 2416 kg ha^{-1} in 2019, although the apparent decline in grain yield was not statistically significant due to high variability between samples and the larger magnitude of the difference between IWG and wheat yields.

1.4.2 Components of grain yield

Fertile tiller percentage and seed size were two yield components that differed the most between IWG and wheat, which likely contributed to differences in grain yield between the crops (Table 3). Intermediate wheatgrass tiller fertility (i.e. the proportion of tillers that produced a mature seedhead) was 25% lower than wheat averaged over all years and decreased from 79% in 2017 to 57% in 2019 while wheat tiller fertility remained above 90% during this period. Averaged across both crops, intercropping red clover increased tiller fertility by 6.8%. Thousand kernel weight was 372% lower for IWG than wheat across three years. Thousand kernel weight trended towards decline for both species over time, but the trend was only significant for wheat. Averaged over three years total tiller count was similar between the two crop species, but IWG tiller count increased from 410 tillers m^{-2} in 2017 to 556 tillers m^{-2} in 2019 while wheat decreased from 514 tillers m^{-2} to 376 tillers m^{-2} over the same period. Seedhead count, which is equivalent to the number of fertile tillers, declined from 488 seedheads m^{-2} in 2017 to 335 seedheads m^{-2} in 2019 for wheat. Intermediate wheatgrass seedhead counts were lowest in 2018 with 195 seedheads m^{-2}, but there was no difference between counts in 2017 (318 seedheads m^{-2}) and 2019 (305 seedheads m^{-2}). The combination of increasing total tiller counts and steady seedhead counts in IWG resulted in the declining fertile tiller percentage that was observed. Total seedhead weight was 121% higher for wheat than IWG and decreased for both species between 2017 and 2019. Seedhead length (177%), and floret count (52%) and seed count (25%) at harvest were all higher for IWG than wheat. A weak but significant interaction was observed between grain crop and intercrop treatments for seedhead length and floret count per seedhead. Intermediate wheatgrass grown in polyculture with red clover produced longer seedheads (20.7 cm vs. 18.7 cm) with more florets per seedhead at harvest (56.5 vs. 47.6) than IWG grown in monoculture, but these differences did not significantly impact the number of seeds per seedhead or seed size. These components did not differ for wheat.

1.4.3 Straw, red clover, and total forage yields

In contrast to the declines in grain yield noted above, IWG straw yield increased from 5541 kg ha^{-1} in 2017 to 7785 kg ha^{-1} in 2019, while wheat straw yield was higher in 2017 (5167 kg ha^{-1}) than it was in 2018 (3072 kg ha^{-1}) or 2019 (3533 kg ha^{-1}) (Table 2). These combined trends in grain and straw production are evident in the harvest index of IWG dropping from 16.1% in 2017 to 4.8% in 2019. Harvest index was highest for wheat in 2018, when wheat straw biomass was at its lowest. Red clover biomass was 244% higher on average in IWG plots than wheat plots. This difference in red clover biomass between grain crop treatments was driven by a large increase from 809 kg ha^{-1} to 3004 kg ha^{-1} in IWG plots between 2017 and 2018. The medium red clover intercrop did not have a significant impact on grain yield, but it did increase total forage production from intercropped plots. When straw and clover biomass were combined for each plot, IWG plots produced 60% more total forage than wheat plots over three years.

Table 2: Results of ANOVA for crop productivity and weed community metrics. Within a factor, treatments sharing the same letter were not significantly different at α=0.05. Simple effects for grain crop by year interactions are reported, with lower- and upper-case letters indicating differences between years for Kernza and wheat, respectively.

Factor	Level	Grain yield	Straw biomass	Harvest Index	Red clover biomass[1]	Forage yield[2]	Weed biomass	Percent perennial weeds	Weed species richness	Weed species evenness
		---------- kg ha^{-1} ----------		kg kg^{-1}	--------------- kg ha^{-1} ---------------			%	species m^{-2}	unitless
Grain Crop	Kernza	478 b	5486	0.085 b	1413 a	6438 a	735	76.4 a	8.04	0.497 b
	Wheat	2807 a	3828	0.388 a	411 b	4024 b	219	38.2 b	10.50	0.604 a
Intercrop	Red clover	1224	4675	0.230	911	5597 a	268 b	57.9	7.25 b	0.530
	No clover	1097	4537	0.243	NA	4675 b	602 a	56.7	11.29 a	0.571
Year	2017	2039 a	5324 a	0.263	632 b	5653 ab	235 b	45.7 b	10.06 a	0.654 a
	2018	728 c	3463 b	0.235	1600 a	4230 b	358 b	68.2 a	7.56 b	0.432 b
	2019	1033 b	5271 a	0.211	502 b	5541 a	765 a	58.0 ab	10.19 a	0.565 ab
Grain Crop x Year										
Kernza	2017	1212 a	5541 b	0.161 a	809 b	5943 b	871 a	45.2 b	11.88 a	0.616
	2018	202 c	3866 b	0.045 b	3004 a	5597 b	602 a	92.1 a	6.25 b	0.351
	2019	441 b	7785 a	0.048 b	425 b	8022 a	757 a	92.0 a	6.00 b	0.526
Wheat	2017	3429 A	5167 A	0.365 A	456 A	5378 A	63 C	46.3 A	8.25 B	0.692
	2018	2644 A	3072 B	0.426 B	196 A	3165 B	215 B	44.3 A	8.88 B	0.514
	2019	2416 A	3533 B	0.374 A	580 A	3866 B	773 A	24.0 A	14.38 A	0.605
Effect						P-value				
Grain Crop		**< 0.001**	**0.0208**	**< 0.001**	**< 0.001**	**0.0051**	0.0518	**< 0.001**	0.1368	**0.0482**
Intercrop		0.2533	0.6854	0.1034	NA	**0.0017**	**<0.001**	0.8231	**< 0.001**	0.4366
Year		**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.0080**	**0.0040**	**0.0058**
Grain Crop x Intercrop		0.7529	0.8853	**0.0368**	**NA**	0.1680	0.1068	0.5665	0.1277	0.4765
Grain Crop x Year		**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	0.7444
Intercrop x Year		0.0965	0.4079	0.1195	NA	**0.0416**[3]	0.7745	**0.0018**[3]	0.1105	0.3445
Crop x Intercrop x Year[4]		0.8084	0.4954	0.8525	NA	0.7017	0.5009	0.6708	0.3035	0.7385

[1] Red clover biomass is not reported for plots that were not interseeded. Any red clover collected in those plots was considered a weed.

[2] Forage yields represent the sum of straw and red clover biomass.

[3] Means for significant intercrop by year interaction for forage yield and perennial weed percentage are reported in the text.

[4] Means for three-way interactions are reported in Appendix A, Table A1.

Table 3: Results of ANOVA for Kernza and wheat components of yield. Within a factor, treatments sharing the same letter were not significantly different at α=0.05. Simple effects for grain crop by year interactions are reported, with lower- and upper-case letters indicating differences between years for Kernza and wheat, respectively.

Factor	Level	Tiller count		Seedhead count		Fertile tillers		Seedhead weight		Seedhead length		Floret count		Seed count		Seed size	
		m^{-2}		m^{-2}		%		g		cm		$seedhead^{-1}$		$seedhead^{-1}$		TKW [1]	
Grain Crop	Kernza	421		272	b	68.6	b	0.309	b	19.7	a	52.1	a	32.6	a	6.7	b
	Wheat	441		408	a	93.4	a	0.682	a	7.1	b	40.9	b	26.0	b	31.4	a
Intercrop	Red clover	429		352		86.2	a	0.437		12.1	a	48.6		29.6		14.2	
	No-clover	433		328		79.4	b	0.482		11.5	b	44.5		28.7		14.7	
Year	2017	462		403	a	88.8	a	0.640	a	13.3	a	50.9	a	37.2	a	16.2	a
	2018	366		297	b	83.3	ab	0.407	b	10.4	c	45.3	ab	26.0	b	14.3	b
	2019	466		320	b	75.2	b	0.372	b	11.8	b	43.4	b	25.1	b	13.0	c
Grain Crop x Year																	
Kernza	2017	410	b	318	a	79.3		0.494	a	23.6	a	59.9	a	47.6	a	7.4	
	2018	297	c	195	b	68.9		0.213	c	17.5	b	46.1	b	24.9	b	6.5	
	2019	556	a	305	a	56.6		0.280	b	18.4	a	50.3	ab	27.2	b	6.1	
Wheat	2017	514	A	488	A	95.8		0.829	A	7.5	A	41.9	A	28.0	A	35.3	
	2018	434	AB	400	B	93.8		0.779	A	6.2	B	44.4	A	27.1	A	31.4	
	2019	376	B	335	B	90.0		0.492	B	7.7	A	36.4	A	22.9	A	27.8	
Effect								**P-value**									
Grain Crop		0.5075		**0.0069**		**< 0.001**		**< 0.001**		**< 0.001**		**< 0.001**		**< 0.001**		**< 0.001**	
Intercrop		0.8607		0.2123		**0.0158**		0.1354		**0.0365**		0.0903		0.5720		0.1841	
Year		**0.0016**		**< 0.001**		**0.0018**		**< 0.001**		**< 0.001**		**0.0356**		**< 0.001**		**< 0.001**	
Grain Crop x Intercrop		0.3928		0.5454		0.7126		0.3655		**0.0442**[2]		**0.0486**[2]		0.1172		0.1005	
Grain Crop x Year		**< 0.001**		**0.0022**		0.3886		**< 0.001**		**< 0.001**		**0.0212**		**< 0.001**		0.7303	
Intercrop x Year		0.3838		0.2031		0.1322		0.1281		0.1938		0.2866		0.1889		0.0944	
Crop x Intercrop x Year [3]		0.3426		0.3048		0.4028		0.6616		0.9947		0.9668		0.7673		0.3313	

[1] Thousand kernel weight in grams.
[2] Means for the significant grain crop by intercrop interactions for seedhead length and floret count are reported in the text.
[3] Means for three-way interactions are reported in Appendix A, Table A2.

Table 4: Weed species rank abundance by crop species, intercrop treatment, and year. Only species contributing to the first 80% of total weed biomass observed for all plots of that treatment combination are included. Weed biomass values were averaged across the four replicates of each treatment combination. LC = life cycle, A = annual, P = perennial. N = number of plots where a weed species was observed for the treatment combination.

		Red Clover Intercrop					**No Clover Intercrop**				
Crop Species	**Year**	**Weed species**	**LC**	**N**	**Biomass**		**Weed species**	**LC**	**N**	**Biomass**	
					kg ha^{-1}	%				kg ha^{-1}	%
Kernza	2017	*Ambrosia artemisiifolia*	A	4	330	45.2	*Lepidium campestre*	A	1	353	26.7
		Convolvulus arvensis	P	2	86	11.8	*Poa trivialis*	P	4	311	23.5
		Poa trivialis	P	3	85	11.6	*Festuca arundinacea*	P	2	149	11.2
		Lepidium campestre	A	2	39	5.3	*Phleum pratense*	P	2	144	10.9
		Polygonum aviculare	A	3	39	5.3	*Ambrosia artemisiifolia*	A	4	75	5.7
		Poa annua	A	2	37	5.1	*Poa annua*	A	2	62	4.7
		Total		4	615	84.3	Total		4	1093	82.7
	2018	*Poa trivialis*	P	4	342	95	*Poa trivialis*	P	3	615	39.2
		Total		4	342	95	*Trifolium pratense*	P	2	598	38.1
							Phleum pratense	P	1	71	4.6
							Total		4	1284	81.9
	2019	*Poa trivialis*	P	4	278	71.2	*Poa trivialis*	P	4	765	49.3
		Phleum pratense	P	2	100	25.6	*Phleum pratense*	P	4	305	19.7
		Total		4	378	96.8	*Lolium multiflorum*	A	1	201	12.9
							Total		4	1272	81.9
Wheat	2017	*Ambrosia artemisiifolia*	A	3	69	62.5	*Ambrosia artemisiifolia*	A	4	62	46.5
		Polygonum convolvulus	A	1	13	11.7	*Convolvulus arvensis*	P	2	20	14.8
		Poa annua	A	3	8	6.9	*Oxalis stricta*	P	4	13	9.8
		Total		4	89	81.1	*Cerastium vulgatum*	P	4	9	7
							Cyperus esculentus	P	2	9	6.4
							Total		4	113	84.5
	2018	*Poa trivialis*	P	4	312	76.3	*Lolium multiflorum*	A	4	211	59.3
		Lolium multiflorum	A	4	76	18.5	*Cerastium vulgatum*	P	3	31	8.6
		Total		4	388	94.8	*Sonchus arvensis*	P	1	19	5.3
							Taraxacum officinale	P	4	19	5.3
							Ambrosia artemisiifolia	A	4	14	3.9
							Total		4	294	82.4
	2019	*Ambrosia artemisiifolia*	A	4	323	47.6	*Ambrosia artemisiifolia*	A	4	493	46.9
		Polygonum convolvulus	A	4	68	9.9	*Polygonum aviculare*	A	4	147	14
		Cyperus esculentus	P	4	49	7.2	*Polygonum convolvulus*	A	4	112	10.6
		Convolvulus arvensis	P	3	49	7.2	*Trifolium pratense*	P	3	83	7.9
		Polygonum aviculare	A	4	49	7.2	*Poa trivialis*	P	1	61	5.8
		Taraxacum officinale	P	2	32	4.7	Total		4	896	85.2
		Total		4	569	83.8					

1.4.4 Weed community structure

Total weed biomass varied by grain crop species, intercrop, and year (Table 2). Weed biomass was higher in IWG plots than in wheat plots in 2017 and 2018.Weed biomass did not change in IWG plots over time, however, but it increased in wheat plots over time such that there was no difference between weed biomass sampled in wheat or IWG plots in 2019. Weed species richness decreased in IWG plots and increased in wheat plots over time. Weed species evenness was higher in wheat plots and varied by year. Red clover provided substantial weed suppression in intercropped plots, reducing both total weed biomass and weed species richness but not affecting evenness.

The percentage of weed biomass from perennial weed species (Table 2) and weed species rank abundance (Table 4) illustrate the community dynamics being affected by crop species and intercrop treatments over time. In 2017 plots of both Kernza and wheat, both monoculture and intercropped, supported a high number of weed species including annual and perennial grasses and forbs. By 2018, however, over 90% of weed biomass in IWG plots consisted of perennial weeds, primarily the perennial grasses *Poa trivialis* and *Phleum pratense*. Weed communities in wheat plots, in contrast, continued to consist of a mix of perennial and annual grasses and forbs throughout the experiment, likely due to the disturbance of annual tillage events. A significant interaction between intercrop and year for perennial weed percentage indicated that perennial weeds increased from 30.2% to 77.2% of total weed biomass in plots intercropped with red clover between 2017 and 2019, while perennial weeds ranged between 53.3 to 61.3% in monoculture plots during that period. Two weedy species that were present in multiple plots were likely introduced by management activities. Monoculture plots of both crop species were invaded by red clover from the adjacent intercropped plots, which was observed to flower and produce seed after post-harvest crop residue mowing each year. Italian ryegrass (*Lolium multiflorum* Lam.) that was planted as ground cover in alleyways also became a prominent weed over time, likely due to seed that was spread when alleys were mowed.

1.5 Discussion

Significant grain crop by year interactions were observed for grain yield, straw biomass, red clover biomass, and weed biomass measurements, and for most components of grain yield (Tables 2 and 3). The frequency of these interactions highlights the differences between the life cycles and reproductive strategies of the two crop species. Overall, IWG allocated less energy to seed production and more to vegetative biomass growth than wheat, an annual crop that has been intensively selected for high seed yield and relatively low vegetative biomass production. The perennial life cycle of IWG also influences its ability to coexist with red clover, a perennial legume, and to outcompete annual and broad-leaved perennial weeds.

1.5.1 Grain yields

IWG produced considerably less grain than annual winter wheat in all three years of this experiment, highlighting a major tradeoff between food production and other ecosystem services obtained from currently available perennial grain crops. Breeding programs have made substantial progress improving IWG seed yield and other agronomic traits such as free-threshability and reduced shattering and lodging, with the first registered variety for grain production released in 2020 (Bajgain et al., 2020). Improving agronomic management practices to increase and maintain IWG grain yield across multiple years has also been identified as a priority by researchers and growers (Duchene et al., 2019; Lanker et al., 2020; Law et al., 2020). Post-harvest management of crop residues (Pugliese et al., 2019) and tiller density (Law et al., 2020; Pinto et al., 2021) have been found to influence IWG grain yield and components of yield, particularly reproductive tiller count, during the following growing season. Evidence from studies on stand thinning suggests that intraspecific competition plays a role in grain yield decline as stands age and plants become crowded (Law et al., 2020; Pinto et al., 2021).

First-year IWG grain yields averaged slightly more than 1200 kg ha^{-1} in our study, which compares favorably to IWG yields of 876 kg ha^{-1} (Hunter, Sheaffer, Culman, & Jungers, 2020) and 1089 kg ha^{-1} (Favre et al., 2019) reported in recent studies. Grain yields in our study decreased significantly from the first to second years, a trend that is supported by other studies (Hunter, Sheaffer, Culman, & Jungers, 2020; Jungers et al., 2017; Tautges et al., 2018). Grain yield did increase slightly from the second to third harvest in our experiment, a trend which has not been previously reported. We hypothesize that very low IWG grain yield in 2018 was not only caused by the general decline in seed production that occurs as IWG stands age, but that it was also influenced by drought during IWG flowering and seed set in 2018 (Figure 1) that impacted IWG growth and reproduction. Drought stress can reduce tillering (Hendrickson et al., 2005) and reproductive effort (Altendorf et al., 2021) of intermediate wheatgrass. IWG grain yield increased from 2018 to 2019, the third year of production when grain yield of IWG is almost always observed to decline

(Fernandez et al., 2020; Tautges et al., 2018) and a year with typical precipitation and GDD for our research site, which provides additional evidence that IWG grain yield in 2018 was impacted by drought. The third-year IWG grain yield of 556 kg ha^{-1} in our study is comparable to yields of 380 kg ha^{-1} (Pugliese et al., 2019) and 514 kg ha^{-1} (Hunter, Sheaffer, Culman, & Jungers, 2020) documented under similar experimental conditions.

Our results also provide a baseline for IWG grain yields under organic management in the northeastern United States. The aforementioned research reporting IWG grain yield was largely conducted with conventional management practices, and comparison with our results suggests that organic management of IWG does not impose a substantial yield penalty. We are aware of only one previous report of IWG grain and straw yields produced without either synthetic fertilizers, pesticides, or both. In that study grain yields averaged 156 kg ha^{-1} in the first production year and 1390 kg ha^{-1} in the second production year, and straw yields were 3982 kg ha^{-1} and 12202 kg ha^{-1} in the first and second years, respectively (Culman et al., 2013). These large increases in both grain and straw yield over time were not observed in our study. This difference may have been influenced by a late planting date that Culman et al. (2013) note delayed establishment of both wheat and IWG in their study and may have impacted the production of reproductive tiller primordia for IWG (Duchene et al., 2021).

Winter wheat yield averaged 2807 kg ha^{-1} between 2017 and 2019, which is lower than yields ranging between 3300 and 5300 kg ha^{-1} reported in other organically managed wheat cropping experiments (Clark et al., 2017; Tosti et al., 2016). Average organic wheat yield was 2684 kg ha^{-1} across New York state in 2017 (National Agricultural Statistics Service, 2020). Continuous cropping of winter wheat is not a common practice in the relatively humid New York climate due to the risk of pathogen buildup over time (Bergstrom & Fulcher, 2017). While we did not quantify pathogens on either wheat or IWG in this experiment it would be expected that disease incidence and severity would be lower on IWG which is largely resistant to common wheat pathogens such as fusarium head blight and bacterial leaf streak (Bajgain et al., 2019). Research on continuous wheat cropping in more arid regions where it is common practice has shown that increasing disease pressure has a negative impact on grain yield over time and even simple two-year crop rotations can ameliorate these issues (Bankina et al., 2013; Sturz & Bernier, 1989). We also observed that weed biomass increased in wheat plots over time, which could have increased competition and impacted wheat grain and straw yields. Fertilizer rates may also have not been sufficient for continuous wheat production (see (Clark et al., 2017; Tosti et al., 2016) for organic winter wheat fertilization comparisons), potentially contributing to the downward trend in wheat yield over time. All plots in our study were fertilized at a rate of 90 kg N ha^{-1} yr^{-1} within the agronomic optimum range for IWG grain production (Jungers et al., 2017). However, due to the typically slower nutrient release rates of organic fertilizers, this rate may have been too conservative for both crops. In one study examining differences between the effects of synthetic and organic N fertilizers on IWG grain yield, synthetic fertilizers (urea and ammonium nitrate) increased grain yield compared to similar rates of composted poultry manure

(Fernandez et al., 2020). Bird damage in 2019 also contributed to the low wheat yield that year.

Decisions to grow wheat after wheat and to fertilize at a rate that was more appropriate for IWG were made to reduce the number of differences in management between the IWG and wheat cropping systems. It should be noted that these decisions impact the interpretation of the comparisons of grain yield and components of yield in a way that favors IWG. Comparisons of grain yield, straw yield, total forage yield and weed community structure would have been confounded, however, if wheat was rotated with another crop. As research on IWG continues we expect that comparisons with more complex annual crop rotations and with perennial grass and legume forages will be conducted that will provide a more holistic view of the benefits and drawbacks of IWG cropping systems.

1.5.2 Components of yield

Fertile tiller percentage and seed size were the two yield components that differed the most between IWG and wheat in this experiment, which were apparent from the start of the experiment but increased over time. Total tiller counts were similar between species but exhibited opposite trends with number of IWG tillers increasing over time while number of wheat tillers decreased. Yield decline in IWG over time appears to be related to decreasing fertile tiller percentage, number of seeds per seedhead, and seed size. These patterns in IWG yield components largely parallel findings from researchers at the University of Minnesota (Altendorf et al., 2021; Hunter, Sheaffer, Culman, & Jungers, 2020). Although IWG's small seed size is increasing because of active breeding programs (DeHaan et al., 2018), its seed was only 20% the size of wheat in this trial. Seed size is only one component of grain yield, however, and balancing multiple yield component traits to increase and sustain IWG seed yield per unit area will likely result in higher grain yield across the multi-year life cycle of IWG (Cattani & Asselin, 2018). Seed size of both species dropped at approximately the same rate over the three years of the experiment. Floret counts per seedhead for IWG measured at harvest in this study were approximately half as many as were reported for IWG from the same breeding cycle measured seven days after flowering (Cattani & Asselin, 2018). This difference is indicative of shattering that occurs before harvest which varies based on environmental conditions and harvest timing, and should be taken into account when estimating the total grain yield potential of IWG. Water stress may have also affected IWG yield components, with tiller count, seedhead count, floret count, and seed count all being their lowest in 2018 when there was very little rainfall between May and mid-July, coinciding with IWG flowering and seed set that typically occurs in late June in New York.

1.5.3 Straw yields

The contrast in grain and straw yields between IWG and wheat illustrates the potential benefits of using IWG as a dual-purpose crop, particularly in a dairy producing state like New York where the value of on-farm forage production can be substantial. While IWG straw production was initially similar to that of wheat it increased by 40% between the first and third years while wheat straw production declined over the same period of time (Table 2). IWG straw collected after grain harvest generally has higher relative forage quality than wheat straw due to the incomplete senescence of stem and leaf tissues and could be a component of mixed rations for beef or dry dairy cattle (Favre et al., 2019). The economic value of the straw alone can cover the cost of producing both grain and forage, decreasing the risk to farmers adopting the crop (Hunter, Sheaffer, Culman, Lazarus, et al., 2020). Straw yields of both crop species were comparable to values reported in the literature (Banowetz et al., 2008; Dick et al., 2018; Favre et al., 2019; Hunter, Sheaffer, Culman, Lazarus, et al., 2020; Pugliese et al., 2019; Zimbric et al., 2020). Further investigation of fertilizer rates and timing should assess tradeoffs in grain and straw production as IWG straw yields readily respond to N fertilizers but it is not clear how fertilization might affect grain yield at different points in the crop's perennial life cycle (Fernandez et al., 2020; Hunter, Sheaffer, Culman, & Jungers, 2020; Hunter, Sheaffer, Culman, Lazarus, et al., 2020; Zimbric et al., 2020).

1.5.4 Weed community structure

Weed management is a critical agronomic challenge for cereal grain production. Our experiment identified major differences between the weed communities of perennial IWG and annual wheat over time that can inform management research and decision making going forward. In a survey of farmers that were early adopters of IWG, weed management was often acknowledged as a major challenge and research priority, but the potential weed suppression provided by a vigorous perennial crop was also cited as a major ecosystem service that farmers were hoping to benefit from (Lanker et al., 2020). In our study the weed communities in IWG plots consisted of a mix of perennial and annual species in the first production year, but were dominated by perennial grass weeds in the second and third years. Species of note include field pepperweed (*Lepidium campestre* (L.) W.T. Aiton), a winter annual broadleaf weed that was not evenly distributed in the field but was highly abundant where present in the first year, and roughstalk bluegrass (*Poa trivialis* L.) and timothy (*Phleum pratense* L.), two perennial grass weeds that are well-adapted to coexisting with IWG. Overall, total weed biomass in IWG plots did not change over time in our experiment, which differs from recent studies finding strong weed suppression by IWG after establishment (Dick et al., 2018; Zimbric et al., 2020). In one of the studies that reported an 88% reduction in weed biomass over three years of IWG production it appears there were few perennial grass weeds at their field site compared to ours, which we suspect is a result of differences in soil seedbank density of the relevant species as crop management was similar between the previous study and ours (Zimbric et al., 2020). Our IWG stand was also likely negatively impacted by droughts in 2016 and 2018, thus reducing establishment vigor and regrowth of IWG, and decreasing crop competitive ability.

Zimbric et al. (2020) reported weed community composition in IWG that was similar to what we observed. They found winter annual broadleaf weeds in the Brassica family to be the dominant species during IWG establishment, and total weed biomass of 754 kg ha^{-1} at the first harvest was similar to the 871 kg ha^{-1} we observed (Zimbric et al., 2020). Moreover, weed community dominance over time also shifted to perennial species in their experiment. These similarities suggest that the IWG cropping system is imposing environmental filters on weed community composition (Garnier & Navas, 2012). One mechanism for the suppression of annual broadleaf weeds could be the relatively high canopy closure in IWG stands after fall regrowth that persists through the germination period of annual weeds the following spring. In our study lower weed species evenness in IWG plots compared with wheat suggests higher dominance by the few perennial grasses that are not outcompeted by IWG. Similarly, lower weed species richness in both IWG and wheat plots interseeded with red clover indicates the weed-suppressive ability of red clover. Weed management has not been studied extensively in IWG production systems and there are many opportunities for research to develop integrated weed management for perennial grain production. There is also the potential to use perennial crops in rotation with annuals as a tool for weed management at the farm and landscape scales. The increasing percentage of perennial weeds, but not total weed biomass, that we observed in IWG over time highlights the importance of planting IWG in fields with low perennial grass weed pressure and developing cultural practices that promote faster IWG establishment and canopy closure. Contamination of IWG seed with perennial grass weed seed should be a concern both to reduce potential weed competition when the IWG seed is planted and prevent quality issues when it is sold as grain (Kruger, 2015).

Observations of weed community structure at different stages in a perennial crop’s life cycle can help inform current and future weed management research. Weed management during IWG establishment, particularly for winter annual broadleaf weeds, warrants attention due to the potential impact of weed competition at that stage on the performance of the IWG stand across multiple years. The Group 4 herbicides 2,4-D, clopyralid, and MCPA have been effective at managing winter annual broadleaf weeds during IWG establishment in ongoing field trials (Keene et al., 2020), and interseeded crops such as red clover may provide weed suppression in organic management systems. Other critical periods of weed control may also need to be better understood in perennial grain cropping systems, including the post-harvest regrowth period that influences perennial grass tiller production and overwinter survival (Duchene et al., 2021; Hayes et al., 2018).

The weed communities of winter wheat under organic management in this experiment were similar to those reported in other studies. In a study conducted on organic winter wheat in Switzerland, Hofmeijer et al. (2019) reported weed biomass at harvest of approximately 250 kg ha^{-1} consisting of many of the same species we observed including dominance by roughstalk bluegrass, Italian ryegrass, and field bindweed (*Convolvulus arvensis* L.). Total weed biomass in wheat plots increased by an order of magnitude over three years in our experiment, coinciding with declines in wheat performance that might indicate the development of negative plant-soil feedbacks in the continuous wheat cropping system (Hol et al., 2013; Menalled et al., 2020).

1.5.5 Effects of interseeded red clover on crop performance and weed communities

Interseeding red clover provided additional ecosystem services in both the perennial and annual cropping systems by suppressing weeds and adding to total biomass production that could be used as forage. Frost-seeded red clover also had no impact on grain yield of either crop species. IWG grown with red clover appeared to have darker green foliage throughout the growing season in 2019, the third year of growth. Differences in leaf color may have been an indicator of higher leaf N content (Baresel et al., 2017) although this was not measured in our experiment. Less leaf rolling was also observed during dry periods when IWG was grown with red clover, which could be a result of hydraulic redistribution (Sekiya et al., 2011) or red clover's ability to moderate soil temperature and reduce surface soil moisture evaporation (Wyngaarden et al., 2015). Red clover did significantly increase the percentage of tillers that produced a mature seedhead across both crops, and increased the number of florets per IWG seedhead. In both cases higher N availability from red clover N fixation is likely the cause. Previous research has shown that legume cover crops that are tilled into soil before planting wheat have been associated with increased reproductive tiller density and grain protein, but lower average kernel weight (Burgess et al., 2014). Increasing N fertilization has also been shown to increase certain yield components, including florets per spikelet, in perennial ryegrass (Young et al., 1996). Intermediate wheatgrass has been shown to obtain nitrogen from intercropped legumes without tillage (Li et al., 2021), and thus similar tradeoffs may be occurring between IWG yield components when intercropped with red clover.

The benefits of including red clover in annual small grain cropping systems are well documented (Gaudin et al., 2013), and based on results from our study it appears that red clover can play a similar role in perennial grain systems. Favre et al. (2019) previously reported that total forage production, crude protein content, and relative forage quality were higher in an IWG-red clover polyculture than IWG in monoculture. First-year IWG grain yield was also lower in the polyculture, however, red clover was planted at the same time as IWG at one of their two experimental locations which may have increased competition from red clover during IWG establishment (Favre et al., 2019). As we did not observe lower IWG grain yields when intercropped with red clover, our results suggest that frost-seeding red clover is a viable strategy for managing inter-crop competition in mixed IWG-clover stands.

Intercropping IWG with other legumes including alfalfa, white clover, and sweet clover can provide net benefits, although the success of perennial polycultures may depend on balancing competition between species within a local environmental context (Dick et al., 2018; Tautges et al., 2018). Understanding the factors that influence these tradeoffs and developing systems that promote inter-species complementarity and facilitation is needed to develop successful perennial polycultures (Duchene et al., 2017).

1.5.6 Limitations and recommendations for future research

Interpretation of the results presented in this paper is limited by the fact that our research only represents a single planting year of IWG. This means that we cannot separate the effects of stand age and weather on crop productivity and components of yield in this study. This is particularly important to acknowledge because there has been little research on the effects of environmental stress on IWG at different stages in its life cycle, with it being likely that stress responses could carry over multiple years in a long-lived perennial grass (Loka et al., 2019). Research on how environmental conditions impact the agronomic performance of IWG certainly deserves more attention, which could be accomplished with coordinated research across different regions where IWG might be grown. In this experiment drought stress appears to have affected IWG grain and straw yield in a very dry year, and low water availability for several weeks after planting may have also slowed IWG establishment. The deep root systems of perennial grasses like IWG should make them more resilient to drought (Thorup-Kristensen et al., 2020), but this advantage may not extend to their reproductive effort (i.e., seed production) in a dry year.

This research represents a first step in developing organic, perennial cropping systems in the northeast United States. Dual-use of both IWG and wheat for grain and straw production is already common practice but will likely have a higher impact on the economic viability of perennial grains like IWG while progress is being made to improve grain yield. Food industry and consumer demand for organically produced IWG is a driver of perennial grain development and results of this study can provide a baseline for further development of organic IWG cropping systems. Specific areas that require further study to improve the performance of organic IWG production include mechanical weed management and optimization of nutrient management practices including evaluating different types, rates, and application timings of organic fertilizers and quantifying nitrogen credits from intercropped legumes. Further research on species mixes for both organic and conventional perennial cropping systems including seeding rates, planting methods and timing (e.g. direct drilling seed vs. frost seeding), plant spacing, and other factors is needed to develop management recommendations for a range of grower objectives (i.e. emphasizing forage versus grain production, weed suppression).

1.5.7 Conclusions

This study provides insight into differences in organic grain and forage production by annual and perennial crops. Annual winter wheat grain yields were considerably higher than those of perennial IWG in each of the three years of the study, a gap that will need to be narrowed as breeding of perennial grains continues (Crain et al., 2021) and agronomic management practices are developed and optimized (Hunter, Sheaffer, Culman, & Jungers, 2020). IWG straw yield also increased and weed biomass in IWG stands did not change over time, while straw yield decreased and weed biomass increased in annual wheat systems. Intercropping IWG with red clover increased total forage production and suppressed weeds compared with a IWG monoculture while also likely providing other services such as N fixation and improved forage quality. Intermediate wheatgrass has the potential to be a successful dual-purpose grain and forage crop that also provides additional ecosystem services, particularly in New York and other places where its high forage production can be utilized in integrated crop-livestock systems.

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CHAPTER 2

MULTI-CRITERIA ASSESSMENT OF THE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF INTERMEDIATE WHEATGRASS GROWN AS A DUAL-PURPOSE GRAIN AND FORAGE CROP

2.1 Abstract

Kernza® intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & Dewey] is a perennial cool-season grass that is being bred for use as a dual-purpose grain and forage crop. The environmental benefits of perennial agriculture have motivated the development of IWG cropping systems and have generated interest in perennial grain food products made with Kernza, but the economic viability and environmental impact of IWG remain uncertain. In this study, we compared three-year cycles of five organic grain production systems: an IWG monoculture, IWG intercropped with medium red clover, a continuous winter wheat monoculture, a wheat-red clover intercrop, and a corn-soybean-spelt rotation. Economic and environmental impact of each cropping system were assessed using enterprise budgets, energy use, greenhouse gas (GHG) emissions, and emergy indices as indicators. Grain and biomass yields, soil health indicators, and values for production inputs including seed, fertilizer, fuel, machinery, labor, grain drying, and natural resources used in these analyses were obtained from experimental data and management records from two separate field experiments conducted in the Fingerlakes region of New York State, USA. Grain yield of IWG was approximately 17% of winter wheat grain yield when averaged over three years. In contrast, total forage harvested from IWG systems was 160% that of wheat systems. Soil health indicators improved at similar rates for IWG and wheat systems. Low grain yield of IWG greatly impacted economic indicators, with break-even farm gate prices for Kernza grain calculated to be 23%

greater than the current price of organic winter wheat in New York. Energy use and GHG emissions from IWG systems was much greater than the annual systems when allocated per kg of grain produced but was much lower when allocated per kg of biomass harvested. Emergy sustainability indices were favorable for IWG systems due to lower estimated soil erosion and fewer external inputs over the three-year crop cycle. Results show that the sustainability of IWG production is highly dependent on how the hay or straw co-product is used, and the extent to which external inputs can be substituted with locally available renewable resources. Integrated crop-livestock systems appear to be the ideal scenario for adoption of IWG as a dual-use perennial grain and forage crop.

2.2 Introduction

Increasing the amount of perennial crops in agroecosystems can enhance many ecosystem services, including diversification of crop products and associated revenue streams, improved soil, air, and water quality, enhanced wildlife habitat, and increased resilience to climate change and extreme weather events (Asbjornsen et al., 2014). Perennial grains in particular have been touted as environmentally sustainable alternatives to annual grain crops such as wheat, barley, rye, and rice that represent greater than 70% of global food production (Crews et al., 2018; Pimentel et al., 2012). Research on perennial grains has emphasized breeding and agronomic management, however, and many perceived or potential environmental and economic benefits of perennial grain cropping systems have yet to be rigorously documented. Tradeoffs have been documented between perennial crop productivity, longevity, and water use efficiency (González-Paleo et al., 2016; Vico and Brunsell, 2018) and it is possible that other substantial tradeoffs exist between different components of economic and environmental sustainability for perennial grains.

Intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & Dewey; hereafter IWG] is a rhizomatous, cool-season perennial grass introduced to North America for use in pastures and forage production (Hendrickson et al., 2005). Varieties of IWG selected for grain yield are being developed using traditional and genomic breeding techniques, with rapid advancement in many agronomic traits (Crain et al., 2021; DeHaan et al., 2018). Concurrently, field trials are providing information on IWG physiology and grain yield potential, crop and cropping systems management, and ecosystem services provided by IWG grown as a perennial grain (e.g., Culman et al., 2013; Duchene et al., 2021; Jungers et al., 2019, 2017; Law et al., 2020; Pinto et al., 2021). As of 2019, commercial production of IWG grain, sold under the trademarked brand ‘Kernza’, has begun in Midwestern states and broader efforts to build market infrastructure are underway (Muckey, 2019).

The perennial nature of IWG increases both the number of functions that the crop can provide in an agroecosystem and the management complexity of the system (Glover et al., 2010). Much of the demand for Kernza grain has focused on organic production (Lanker et al., 2020), partly because of the organic certification’s alignment with other environmental sustainability attributes of the crop but also because there are currently no pesticides registered for use in Kernza production (Keene et al., 2020). Managing IWG crops for dual-purpose production of both grain and forage has been identified as way to lessen the economic disadvantage of low IWG grain yields relative to annual small grain crops (Hunter et al., 2020b).

Management strategies can also prioritize the enhancement of other agroecosystem functions, such as soil health regeneration, nitrogen fixation, or pest suppression, by rotating IWG with annual crops, strategically locating IWG stands in areas prone to soil erosion and runoff, or growing IWG in polyculture with forage legumes (Duchene et al., 2019; Ryan et al., 2018). Red clover (*Trifolium pratense* L.) is frequently interseeded with annual small grains in organic cropping rotations in the Northeast US to provide nitrogen fixation, microclimate regulation, and weed suppression (Bybee-Finley and Ryan, 2018; Gaudin et al., 2013), and IWG-red clover intercrops have been found to produce more and higher quality forage (Favre et al., 2019).

Multi-criteria assessment is a useful tool for developing management strategies and tactics in agricultural systems where maximizing crop yield or profitability is not the sole management objective (Davis et al., 2012; Giuliano et al., 2016; Vasileiadis et al., 2013). Trends in cereal grain production, including the adoption of alternative crops and diversified cropping systems, are driven by economic, social, and policy factors that often boil down to risk management and perceived benefits to farmers (Maaz et al., 2018). Farmer's reported motivations for growing perennial grain crops such as IWG include profitability, improved soil health and water quality, reduced reliance on purchased inputs, improved weed management, and the ability to graze livestock or produce forages (Lanker et al., 2020; Wayman et al., 2019). Demand for Kernza grain for both small-scale artisan products (e.g., craft brewing, artisanal bakeries, local restaurants) and large-scale consumer packaged goods (e.g., Cascadian Farms' toasted Kernza flakes breakfast cereal) has been driven by the crop's perceived environmental benefits (Muckey, 2019). Providing farmers with information on crop productivity benchmarks, possible market prices for Kernza grain, and the magnitude of environmental impacts of Kernza cropping systems will allow them to make more informed decisions about the risks and benefits of adopting Kernza as a grain crop. This information will also be useful for developing policy and financial incentives for perennial crop production that account for environmental impacts. In the context of these competing motivations for IWG production, multi-criteria assessment of the agronomic, economic, and environmental characteristics of the crop will facilitate the development of management recommendations, supply chains, and markets.

While assessing the effects of management decisions on agronomic productivity, that is, grain and forage yields, is a critical step in the development and adoption of IWG cropping systems, it is also important to consider the impact on other indicators of sustainability such as soil health, profitability, energy use, and greenhouse gas (GHG) emissions. Soil health, defined as “the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans” (USDA NRCS, 2020), underpins agricultural production but managing soils to provide multiple services often requires tradeoffs (Norris et al., 2020). Enterprise budgets and sensitivity analysis are commonly used tools for assessing the impact of farm management alternatives on profitability, allowing for the efficient allocation of resources to achieve economic objectives (Kletke, 2019). Energy analysis evaluates a production system’s energy efficiency by accounting for direct (e.g., fuels and electricity used on-farm) and indirect (e.g., energy used in the production and transportation of crop seed, fertilizers, and other inputs) sources of energy used to generate crop products (Hoffman et al., 2018). The quantification of GHG emissions is often included in energy analyses due to the impact of fossil fuel consumption on global climate change (Camargo et al., 2013). Emergy evaluation is an environmental accounting system that compares the sustainability of production systems based on the embodied energy contained in inputs and thus contributed to production of goods and services by the system (Odum, 1996). The emergy method goes even further than energy analysis in accounting for indirect sources of energy by quantifying both economic and environmental inputs to a production system, thereby emphasizing environmental impacts and the externalities that arise from overreliance on economic indicators (Hercher-Pasteur et al., 2021). By assessing IWG relative to other annual cropping systems using the various indicators that are generated by these different types of analyses a more holistic view of the potential benefits and drawbacks of growing IWG can be developed.

The objective of this study was to perform a multi-criteria assessment of the agronomic productivity, economic profitability, and environmental sustainability of IWG grown for dual-use grain and forage production under organic management. The effects of intercropping medium red clover with IWG and annual winter wheat on crop productivity and indicators of soil health were measured in a field experiment conducted in the Fingerlakes region of New York State, USA. We hypothesized that perennial IWG would produce less grain but more forage biomass than winter wheat, and that including red clover as an intercrop would increase forage biomass harvested from both systems. We also hypothesized that soil health indicators would improve more quickly in IWG systems than in wheat systems. Empirical data from the experiment comparing IWG and wheat production systems and a separate field experiment on organic grain crop rotations conducted in the same region were also used to compare IWG to continuous winter wheat and corn-soybean-spelt cropping systems using several indicators of economic and environmental sustainability. Enterprise budgets were created to estimate production costs and revenues based on management records from the two field experiments and aggregate data on crop and input prices from the US Department of Agriculture and other sources. Due to lack of reliable prices for IWG grain as market infrastructure develops, economic indicators assessed were break-even prices for IWG grain after accounting for all production costs and revenue from hay sales, and grain prices that would allow net present value (NPV) of the IWG cropping system to match that of the annual grain cropping systems. Environmental impact was assessed using indicators of soil health, farm energy use and greenhouse gas emissions, and indicators of whole-system sustainability calculated using the emergy method.

2.3 Methods

Data were collected from two separate field experiments, both of which were conducted at the Cornell Musgrave Research Farm, Aurora, New York, USA (42.7222 N, 76.6636 W). Soil types at the site are Honeoye and Lima series silt loams with average pH of 7.5 and 3.2% organic matter. Mean annual temperature was 9.1°C and mean annual precipitation was 918 mm based on the 1981-2010 NOAA 30-year climate averages for this site (Arguez et al., 2012).

2.3.1 Field experiment description and data collection

The main experiment informing the analyses in this paper was conducted between 2016 and 2019 to compare perennial and annual small grain cropping systems. Annual temperature was higher than the 30-year average and precipitation varied during the experiment, with substantial droughts occurring in 2016 and 2018 (Figure 2). The experiment was a split-plot randomized complete block design with four blocks. Main plot treatments were Kernza IWG and hard red winter wheat (cv 'Warthog'). IWG seed was obtained from a breeding population after the third cycle of selection for increased seed size and yield per plant (DeHaan et al., 2018). Split-plot treatments were interseeded medium red clover and a no clover control.

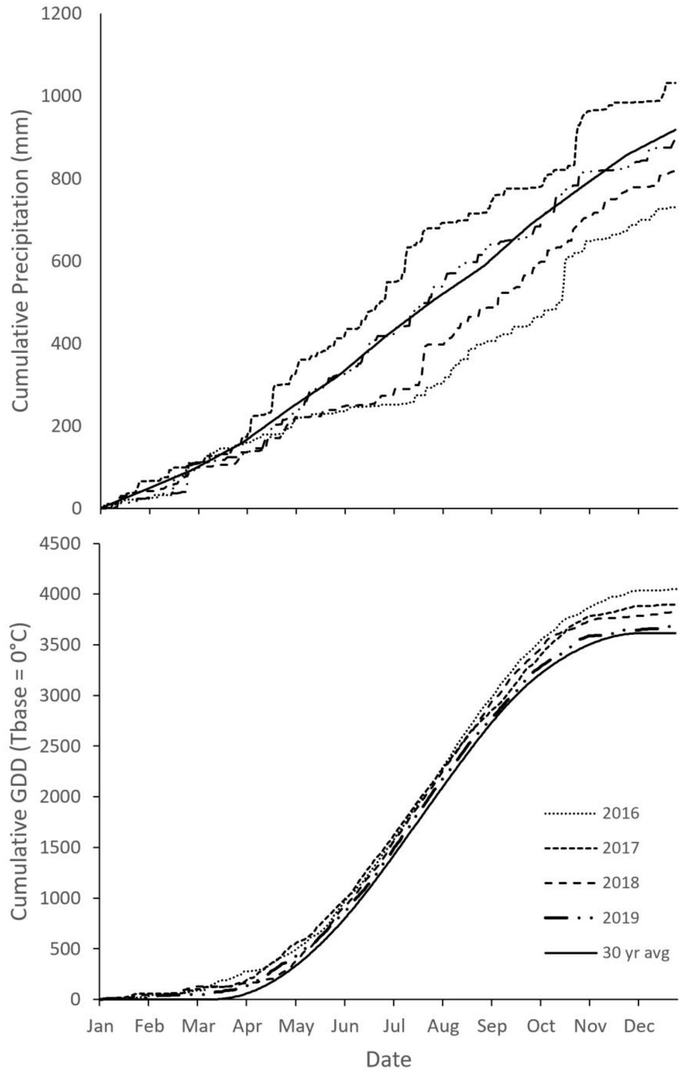

Figure 2: Cumulative precipitation and growing degree days (0°C base) observed at Aurora, New York, USA between 2016 and 2019.

Field operations included primary and secondary tillage, fertilizer application, planting, harvesting, and post-harvest straw management for all plots (Table 5). Seedbed preparation for the experiment included moldboard plowing followed by disking and cultipacking. A false seedbed was used to manage weeds prior to crop seeding by allowing two weeks for weeds to germinate between primary tillage on August 16 and secondary tillage, fertilization, and seeding operations on August 30 and 31. Both grain crops were planted on August 31, 2016 using a John Deere 1590 grain drill (John Deere US, Moline, Illinois, USA) with 19 cm row spacing. The seeding rate for IWG was 16.8 kg ha^{-1} and seeding depth was 1.25 cm, whereas the seeding rate for wheat was 107.6 kg ha^{-1} and seeding depth was 2.5 cm. Red clover seed was frost-seeded in March of 2017 by broadcasting into subplots of both the IWG and wheat treatments at a seeding rate of 22.4 kg ha^{-1}.

Table 5: Schedule of field operations for IWG and wheat production systems between 2016 and 2019 in Aurora, New York.

Field Operation	**Equipment Utilized**	**2016**	**2017**	**2018**	**2019**
Primary tillage	Moldboard plow	Aug. 16	-	-	-
Fall fertilizer application	Drop spreader	Aug. 30	Sep. 13	Sep. 13	-
Secondary tillage and planting	Disk harrow, cultipacker, grain drill	Aug. 31	Sep. 14	Sep. 14	-
Frost seeding red clover	None (broadcast by hand)	-	Mar. 29	Mar. 22	Mar. 19[1]
Spring fertilizer application	None (broadcast by hand)	-	Apr. 19	Apr. 20	Apr. 25
Wheat grain & straw harvest	Plot combine, flail chopper	-	July 19	July 11	July 15
IWG grain & straw harvest	Plot combine, flail chopper	-	Aug. 9	Aug. 15	Aug. 23

[1] Red clover was frost seeded in 2019 into wheat plots in only

Soil and crops were managed organically according to the USDA National Organic Program regulations; however, the field was not certified organic. All purchased seed was certified organic, approved fertilizers were utilized, and no prohibited inputs were applied. Composted chicken manure (5-4-3, Kreher Family Farms, Clarence, New York, USA) was broadcast at a rate of 900 kg ha^{-1} in both autumn and spring of each year, with the goal of applying 90 kg N ha^{-1} annually to approximate agronomically optimum N rates for IWG (Jungers et al., 2017). Grain was harvested immediately after quadrat sampling each year (details below), and crop residues above 10 cm in height were flail chopped and removed one to two weeks after grain harvest of each crop. In 2017 and 2018, wheat was re-planted in the same plots in mid-September. Continuous winter wheat crops are not typically grown commercially in New York, but this simplified annual small grain cropping system was selected to evaluate the effects of continuous cropping and standardize the comparison with the perennial IWG system. Seedbed preparation for replanting was the same as in 2016. Red clover was re-seeded in both IWG and wheat plots in March 2018 but was only reseeded in wheat plots in March 2019 due to the vigorous clover growth in IWG plots in 2018.

Agronomic data were collected from the IWG and wheat experiment in 2017, 2018, and 2019. Two 0.5 m^2 quadrats were sampled in each subplot at crop maturity, which varied by grain crop. Plot edges were avoided. Within each quadrat all crop plants were clipped at the soil surface and separated into seedheads and stems. All clover plants larger than 2.5 cm in diameter or height were also harvested at the same time as crop harvest. Biomass from the two quadrats per subplot was then combined into a single sample representing 1 m^2 of area. Biomass samples were dried for at least five days at 65°C before weighing. Seedheads were weighed intact, threshed, and dehulled using a hand deawner/debearder (Hoffman Manufacturing Inc., Corvallis, Oregon, USA), and reweighed as naked seed. All IWG and wheat yield estimates were normalized to 13.5% moisture content. For more detail on the management and agronomic data collection for the experiment comparing IWG and wheat see Law et al. (2021).

Soil samples were collected from the top 20 cm of the soil profile in the IWG and wheat plots each year between 2016 and 2019 to assess any changes in indicators of soil health. Samples were collected with a 10.8 cm diameter core probe in early September of each year. In 2016, this sampling was carried out after all tillage operations had occurred and IWG and wheat had been planted. In 2017 and 2018, sampling occurred after all crops had been harvested but before wheat plots were tilled and replanted. In 2019, sampling occurred after all crops were harvested. Five cores were collected from random locations in each subplot of the experiment. Aggregate samples for each subplot were homogenized and weighed in the field. One kg of each aggregate sample was retained for further analyses. These subsamples were kept in cold storage at 4°C until they were sieved to 2 mm within two weeks of collection. Approximately 50 g of sieved soil from each sample was oven-dried at 60°C until a constant weight was recorded to estimate gravimetric soil moisture. Soil moisture and the soil core volumes and weights recorded in the field were used to calculate soil bulk density. The remaining soil for each sample was air dried at 23°C, then analyzed for wet aggregate stability, soil respiration, and active (permanganate-oxidizable) carbon using protocols from the Comprehensive Assessment of Soil Health (Moebius-Clune et al., 2016).

2.3.2 Corn-soybean-wheat cropping system

Data from a separate, earlier field experiment described by Caldwell et al. (2014) were used to create enterprise budgets and perform sustainability analyses for a corn-soybean-spelt cropping system that is representative of organic cash grain farmers in upstate New York. This experiment was initiated in 2005, however, crop management and productivity data used in this study were collected between 2008 and 2010, representing the first full corn-soybean-spelt rotations after the three-year organic transition period. Field operations included annual primary and secondary tillage for seedbed preparation, planting, one to three tine weedings and one to four cultivations per year, fertilizer applications in the corn and spelt years, harvesting, and mowing of crop residues. Crops were harvested with a combine (Case IH 1644, Grand Island, Nebraska, USA) that recorded weight and percent moisture of the grain for each plot. Grain yields were standardized to 15% moisture for corn and 13% moisture for soybean and spelt. Data reported here are from the "High Fertility" treatment that applied 2 Mg ha^{-1} poultry manure in addition to incorporation of a red clover green manure before corn and variable application of compost and commercial organic fertilizers to meet recommended rates for soybean and spelt based on measured soil nutrient availability. This system represented the typical organic fertility management practices for corn used by local farmers at the time these data were collected. For more detailed information on management practices and data collected in this experiment, see Caldwell et al. (2014).

2.3.3 System boundaries, assumptions, and input definitions

All five cropping systems (IWG monoculture, IWG-red clover intercrop, winter wheat monoculture, wheat-red clover intercrop, and corn-soybean-spelt rotation) were evaluated using a cradle-to-farm gate boundary. Analyses assume that on-farm processing was limited to grain drying and hay baling and all crops were sold as commodities and transported by the buyer. Inputs to cropping systems included grain crop and clover seed, poultry litter, diesel fuel, machinery, and labor used for field operations, energy used for grain drying, land, and natural resources (soil, sun, wind, and rain) necessary for crop production. Values for these inputs were calculated using management logs from each of the two experiments, except for frost-seeding of red clover and spring fertilizer applications which were done by hand for individual plots in the experiment but were calculated as if they had been done with a drop or spinner spreader across a full field. Fuel consumption and labor hours used in enterprise budgets and emergy calculations are based directly on values recorded during field operations by the researchers, while values for these inputs used in the energy and GHG analyses were calculated using the Farm Energy Analysis Tool (FEAT) model (Camargo et al., 2013). Soil erosion rates were estimated based on values from Nearing et al. (2017) with years where tillage was conducted using 2012 values for cultivated cropland in the USA and values for IWG in years after establishment considered to be the same as Conservation Reserve Program land planted with perennial vegetation. Values for other farm infrastructure, management, and overhead were not included in analyses. While the corn-soybean-spelt data were collected between 2008 and 2010, prices for inputs and crop sales for all systems were based on conditions between 2016 and 2019 when the IWG and wheat experiment was conducted to allow for equal comparisons between all systems.

2.3.4 Enterprise budgets

Enterprise budgets were developed for all five cropping systems based on measured grain and straw yields and purchased inputs including field operations, seed, fertilizer, land rental, and organic certification fees. All returns were calculated on a NPV basis with a 5% annual discount rate starting in 2017. An opportunity cost equal to 5% of annual production costs was included to account for alternative uses of capital. Organic grain and hay prices were calculated using aggregate farm sales data from USDA National Agricultural Statistics Service reports (National Agricultural Statistics Service, 2020a). Intermediate wheatgrass biomass at harvest was considered to be a fair quality hay based on typical forage quality of IWG from The Land Institute's breeding program (Favre et al., 2019) and USDA Hay Quality Designation Guidelines. Wheat straw prices were obtained from weekly Pennsylvania hay auction reports (mymarketnews.ams.usda.gov/viewReport/1716). Field operation costs were based on 2018 Ohio farm custom rates, which account for machinery, labor, and fuel costs (Ward and Barker, 2018). Costs for wheat, corn, soybean, and clover seed and organic fertilizers represent typical prices paid by researchers, so may be conservative estimates relative to costs to farmers who may receive discounts for bulk purchases. The price of registered Kernza IWG seed was obtained from colleagues at The Land Institute and is representative of cost to farmers. Land rental costs for New York were obtained from USDA survey data (National Agricultural Statistics Service, 2019).

Several IWG grain price estimates were calculated based on comparisons to the annual cropping systems and scenarios that varied IWG grain and forage yields, or wheat grain and straw prices. Break-even IWG grain prices were calculated by equating total revenues for grain and hay to total production costs. Comparisons were made to the wheat-clover and corn-soybean-spelt systems by varying IWG grain price to match NPV of the IWG system to those systems. Sensitivity analysis of the effect of variation in IWG grain and forage yields on IWG grain price was conducted using a range of crop production values from on-farm trials in New York and published agronomic research on IWG. This analysis used NPV of the corn-soybean-spelt system, representing a likely alternative agricultural land use, as the benchmark for calculating IWG grain price. Sensitivity analysis was also conducted on the influence of wheat grain and straw prices on IWG grain price required to match NPV of the wheat-clover system. In this analysis IWG hay price was matched to hypothetical wheat straw prices to simulate high- and low-value markets for animal feeds.

2.3.5 Energy usage and greenhouse gas emissions

Energy use and greenhouse gas emissions were estimated for each cropping system using the Farm Energy Analysis Tool (FEAT; Camargo et al., 2013). The FEAT model has previously been used to evaluate the impacts of management decisions on organic grain and dairy production systems in the northeastern United States (Hoffman et al., 2018; Malcolm et al., 2015). We used a version that was parameterized to account for the recycling of animal wastes as fertilizers in organic cropping systems (Hoffman et al., 2018). Production inputs and crop yields from the two field experiments were used to define the five cropping systems in the model. Direct energy use and GHG emissions were calculated for fuel and labor used in field operations, transportation of inputs to the farm, grain drying, and for emissions from fertilizer applications and crop residue decomposition. Intergovernmental Panel on Climate Change Tier 1 methods were used to estimate N_2O emissions (Eggleston et al., 2006). Indirect sources of energy use and GHG emissions were calculated for production of all material inputs including seed, poultry litter, fuel, and farm machinery. In most cases, inputs were converted to energy and GHG emission values using default conversion factors included in the FEAT model that represent averages of values reported in the literature. Intermediate wheatgrass seed energy was based on measured values for forage grass seed (Ortiz-Cañavate and Hernanz, 1999). Machinery weights, fuel use, and labor requirements for granular fertilizer application, broadcast seeding of red clover, and complete forage harvest were parameterized using information from extension publications cited in the original model (Hanna, 2001; Lazarus, 2021; Ortiz-Cañavate and Hernanz, 1999). Energy use and emissions were allocated to production using three methods: per hectare of cropland, per kg of harvested crop biomass, and per kg of grain yield. Different allocations allow the comparison of the different cropping systems while accounting for differences in crop yields and the impact of dual-use systems that produce both grain and hay or straw as co-products.

2.3.6 Emergy evaluation

The whole-system sustainability of the five organic cropping systems was assessed using emergy evaluation, a method of accounting for the embodied energy utilized within a production system (Odum, 1996). All inputs necessary for production were estimated based on management records for the two field experiments that included seeding and fertilizer rates, labor, machinery, and fuel required for field operations, estimated annual soil erosion rates, and values for solar radiation, precipitation, and wind observed at the research farm's weather station (Figure 3). Inputs were converted from their observed unit values to solar emjoules (seJ), a standard unit of embodied energy, using unit emergy values reported in the emergy literature (see Appendix B, Tables B11-B15 for sources of conversion factors). These emergy flows were each categorized as renewable local resources, non-renewable local resources, or non-renewable imported inputs. In the context of emergy evaluation, local indicates that a resource is obtained within the boundaries of the system being evaluated, in this case, the research farm where the field experiments were conducted, while imported resources originate outside of the system. Renewable resources are freely available from the environment and are self-regenerating within the time scale of the evaluation. In this study these included solar radiation, the chemical energy of rain, and the kinetic energy of wind. Non-renewable local resources are available from the local environment but do not regenerate within the time scale of the evaluation. In this study soil erosion was the sole emergy flow within this category. Non-renewable imported resources are obtained outside of the system such as energy, goods, and services that are utilized in production. Imported resources are typically considered non-renewable because they represent feedbacks from the economy that are inherently limited (Ulgiati and Brown, 1998).

Several emergy-based sustainability indicators were calculated based on these emergy flows (Table 6). Specific Emergy is a relative indicator of a system's production efficiency, as it represents the emergy expended to produce one unit of product, in this case grain and hay or straw. Lower specific emergy indicates a more efficient use of inputs and is useful to compare systems that generate similar outputs, but it does not account for differences in the sustainability of inputs. Thus, systems that substitute purchased and non-renewable inputs for locally available renewable resources may have lower specific emergies for products but have a larger environmental impact. The Emergy Yield Ratio (EYR) is also a relative indicator of production efficiency that is comparable to the concept of energy return on investment, representing how efficiently a system is able to harvest local sources of emergy per unit of imported emergy (Ulgiati et al., 1995). The Environmental Loading Ratio (ELR) is the ratio of emergy flows from non-renewable and imported sources to the emergy flows from renewable resources. The ELR indicates the relative level of environmental stress that is created by a production system, accounting for diffuse environmental impacts of processes needed to supply inputs that may occur at a variety of spatiotemporal scales relative to the system (Ulgiati and Brown, 1998). An ELR greater than ten indicates a system that is highly dependent on flows of non-renewable emergy, while an ELR less than one indicates a system that is driven by locally available resources (Brown and Ulgiati, 2004). The Emergy Sustainability Index (ESI) is the ratio of EYR to ELR, indicating the economic contribution of a product per unit of environmental loading (Ulgiati and Brown, 1998). An ESI less than one indicates that a production system is a net-consumption process that is driven by non-renewable, typically imported, inputs, while an ESI greater than one indicates that a system contributes more emergy to the economy than it consumes (Brown and Ulgiati, 2004).

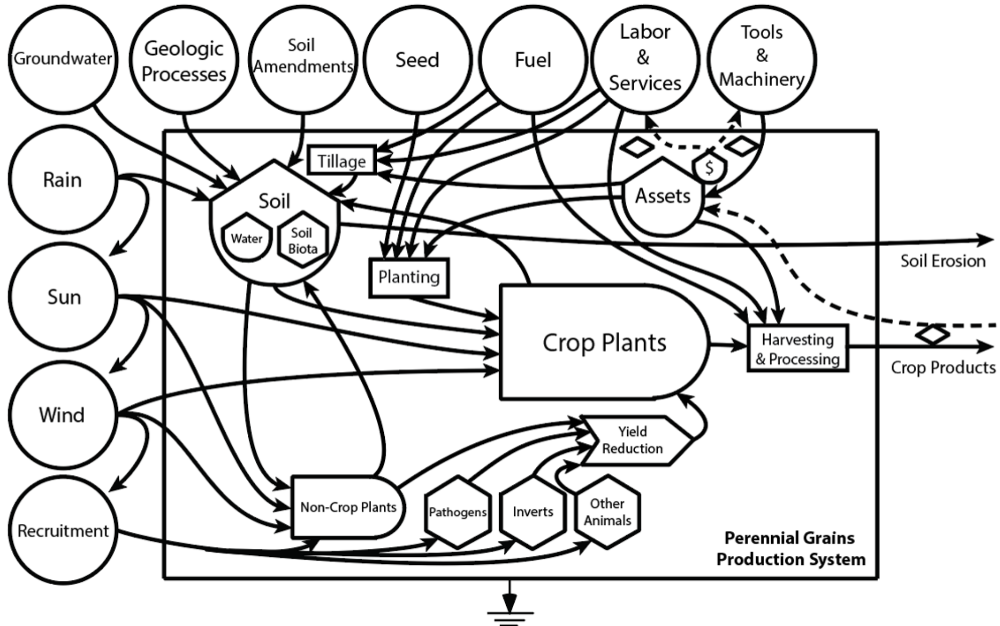

Figure 3: Emergy flow diagram for a typical grain production system.

Table 6: Description of emergy-based sustainability indicators. R is the subtotal of emergy flows from renewable local resources (sun, wind, rain), N is the subtotal of non-renewable local resources (soil erosion), and F is the subtotal of purchased or imported resources (feedback from the economy).

Emergy indicator	**Abbreviation**	**Equation**
Specific Emergy	-	(R + N + F) / mass of product
Emergy Yield Ratio	EYR	(R + N + F) / F
Environmental Loading Ratio	ELR	(F + N) / R
Emergy Sustainability Index	ESI	EYR / ELR

2.3.7 Statistical analysis

Statistical analysis of crop yields and soil health indicators was conducted using linear mixed effects models in R statistical software version 4.1.0 (R Core Team, 2021). Models were created for grain yield, vegetative crop biomass, clover biomass, soil bulk density, wet aggregate stability, soil respiration, and active carbon indicators using the 'lme4' package (Bates et al., 2015) with crop species, intercrop, and year treated as fixed effects, and block and main-plot treatment as random effects to account for plot and split-plot randomization. Assumptions of normally distributed errors and homogeneity of variance were checked with Shapiro-Wilk and Levene's tests, respectively. Grain yields, crop biomass, and clover biomass were log transformed to satisfy assumptions of normality. Treatment means reported for these variables represent back-transformed estimated marginal means calculated with the 'emmeans' package (Lenth, 2020). Post-hoc comparisons of means were conducted using Tukey's HSD as implemented in the 'emmeans' package. All statistical tests used $\alpha = 0.05$ as the threshold for significant effects.

2.4. Results and discussion

2.4.1 Soil health indicators

Soil health indicators measured in the topsoil generally improved over time in both the Kernza and the wheat systems (Table 7). Soil bulk density was slightly lower in systems that included red clover (1.25 g cm^{-3}) than in systems without red clover (1.28 g cm^{-3}) when averaged across all sampling dates. Bulk density increased from 1.23 g cm^{-3} to 1.32 g cm^{-3} in wheat plots between 2016 and 2019 but did not change significantly in Kernza plots, likely due to two additional tillage events in the wheat systems. Trends of increases in wet aggregate stability, soil respiration, and active carbon were similar between IWG and wheat systems over time (Table 7). Averaged across all grain crop by intercrop treatments, aggregate stability increased from 31.3% in 2016 to 48% in 2017 and 45.9% in 2018, before decreasing to 35.8% in 2019. Soil respiration increased more than two-fold from 0.486 mg CO_2 g^{-1} soil at baseline sampling in 2016 to 1.086 mg CO_2 g^{-1} soil at the end of the first growing season in 2017, then remained close to the higher level in 2018 and 2019. Active carbon increased from 566 mg C kg^{-1} soil in 2016 to 762 mg C kg^{-1} soil in 2019. When changes in these indicators over time are normalized to the baseline values collected at the start of the experiment it appears that active C was increasing at a higher rate in IWG plots and plots interseeded with red clover, while soil respiration increased more quickly in wheat plots, although these trends were not statistically significant. Soil erosion was estimated to average 2.8 Mg ha^{-1} yr^{-1} for IWG and 6.7 Mg ha^{-1} yr^{-1} for wheat and corn-soybean-spelt systems.

Table 7: Results of ANOVA for soil health indicators. Treatment means are presented in their standard units alongside percentages of the 2016 baseline indicator levels (%BL) to show relative change in indicators over time. Within a factor, treatments sharing the same letter were not significantly different at α=0.05. Simple effects for grain crop by year interactions are reported, with lower- and upper-case letters indicating differences between years for Kernza and wheat, respectively.

Factor	**Level**	**Bulk density**			**Aggregate stability**			**Respiration**			**Active C**		
		g cm^{-3}	%BL		%	%BL		mg CO_2 g^{-1}	%BL		mg C kg^{-1}	%BL	
Grain Crop	Kernza	1.26	101	a	38.8	144	a	0.828	196	a	649	133	a
	Wheat	1.28	105	a	41.7	139	a	0.847	201	a	693	122	a
Intercrop	Clover	1.25	101	b	40.0	142	a	0.838	199	a	664	129	a
	No Clover	1.28	105	a	40.5	141	a	0.838	198	a	677	126	a
Year	2016	1.24	-	b	31.3	-	b	0.486	-	d	566	-	d
	2017	1.33	107	a	48.0	158	a	1.086	127	a	705	127	b
	2018	1.20	97	b	45.9	149	a	0.788	118	c	650	118	c
	2019	1.30	105	a	35.8	117	b	0.991	138	b	762	138	a
Grain Crop x Year													
Kernza	2016	1.25	-	a	29.4	-	a	0.497	-	c	532	-	a
	2017	1.27	101	a	45.9	158	a	1.060	215	a	681	131	a
	2018	1.24	99	a	44.0	151	a	0.834	169	b	642	112	a
	2019	1.28	102	a	35.8	123	a	0.998	203	a	741	143	a
Wheat	2016	1.23	-	B	42.9	-	A	0.609	-	D	600	-	A
	2017	1.39	113	A	59.8	157	A	1.247	237	A	729	122	A
	2018	1.17	95	B	57.4	147	A	0.877	157	C	658	112	A
	2019	1.32	107	A	45.5	112	A	1.118	208	B	784	132	A
Effect		P-value											
Grain Crop		0.7413			0.5973			0.7913			0.5731		
Intercrop		**0.0404**			0.6799			0.9951			0.2950		
Year		**< 0.001**			**< 0.001**			**< 0.001**			**< 0.001**		
Grain Crop x Intercrop		0.1980			0.8733			0.3155			0.2766		
Grain Crop x Year		**< 0.001**			0.6236			**0.0099**			0.5131		
Intercrop x Year		0.5572			0.7549			0.3869			0.5267		
Grain Crop x Intercrop x Year		0.6948			0.6372			0.7653			0.9257		

These combined results suggest that the positive soil health impacts of IWG compared with annual grain crops that have been observed in other studies (Culman et al., 2013; Sprunger et al., 2019) may depend on a number of environmental and management variables. Soil type, depth of soil sampling, number of seasons IWG is grown, intercropping, other crop management decisions, and the annual cropping system that IWG is compared with will all likely impact the magnitude of effects and how quickly they can be detected. For example, active C was found to be higher in IWG compared with continuous annual wheat after four years when both were grown with synthetic fertilizers and pesticides, but no difference was observed when both crops were fertilized with poultry manure and no pesticides were applied (Sprunger et al., 2019). In the same experiment mineralizable C, a less-processed form, was higher in IWG soils fertilized with poultry manure, which when combined with much higher total root biomass and C:N ratios for IWG suggested that slower processing of organic matter by soil microbes might make differences in soil health indicators difficult to detect between perennial and annual grain crops in the short-term, but with high potential for soil carbon accumulation over a longer period of perennial crop growth (Sprunger et al., 2019). Following a disturbance such as tillage, perennial agroecosystems also go through a series of successional changes that will impact functionality and ecosystem services over time (Crews et al., 2016). Higher allocation of resources to belowground growth allows IWG roots to utilize a much larger percentage of the soil profile than annual grains and stimulate growth of soil fungal communities, particularly arbuscular mycorrhizal associations, but these differences are not apparent within the first year of growth and are much more pronounced in deeper soil layers (Duchene et al., 2020). We suspect that if we had sampled deeper in the soil profile, or over a longer period, that we would have observed larger differences between the perennial IWG and annual wheat systems.

2.4.2 Crop yields and economics

Large differences were observed between IWG and wheat crop productivity, with wheat producing 487% more grain than IWG over three years, while IWG produced 48% more total forage (sum of IWG and clover biomass) on average during the same period (Table 8). Intermediate wheatgrass grain yield declined 500% between the first and second harvests, then rebounded slightly at the third harvest, while IWG crop biomass increased 40% from the first to third harvests. Wheat crop biomass decreased 31% from the first to third harvests. Wheat grain yield trended lower from year to year, but the differences were not statistically significant (Table 8).

Total grain yield for the IWG systems averaged 478 kg ha^{-1} yr^{-1} and for wheat systems averaged 2807 kg ha^{-1} yr^{-1} (Table 8). Grain yields for organic winter wheat were comparable to the New York state average of 2684 kg ha^{-1} in 2019 (National Agricultural Statistics Service, 2020a). First year grain yields of IWG of 1200 kg ha^{-1} in our experiment were at the higher end of yields reported in the literature that range between 108 kg ha^{-1} (Clark et al., 2019) and ~1300 kg ha^{-1} (Fernandez et al., 2020). In contrast, IWG vegetative biomass production was relatively low compared with other published research, with our highest value of 8412 kg ha^{-1} from a third harvest when intercropped with red clover appearing similar to the lowest first harvest values reported in a recent forage production study (Hunter et al., 2020b). For a more thorough evaluation and discussion of crop yields from the IWG and annual wheat systems, see Law et al. (2021).

Table 8: Results of ANOVA for crop productivity indicators. Within a factor, treatments sharing the same letter were not significantly different at α=0.05. Simple effects for grain crop by year interactions are reported, with lower- and upper-case letters indicating differences between years for Kernza and wheat, respectively.

Factor	**Level**	**Grain yield**		**Crop biomass**		**Red clover biomass[1]**		**Forage yield[2]**	
		------------------------ kg ha^{-1} -------------------------							
Grain Crop	Kernza	478	b	5486		1413	a	6438	a
	Wheat	2807	a	3828		411	b	4024	b
Intercrop	Red clover	1224		4675		911		5597	a
	No clover	1097		4537		NA		4675	b
Year	2017	2039	a	5324	a	632	b	5653	ab
	2018	728	c	3463	b	1600	a	4230	b
	2019	1033	b	5271	a	502	b	5541	a
Grain Crop x Year									
Kernza	2017	1212	a	5541	b	809	b	5943	b
	2018	202	c	3866	b	3004	a	5597	b
	2019	441	b	7785	a	425	b	8022	a
Wheat	2017	3429	A	5167	A	456	A	5378	A
	2018	2644	A	3072	B	196	A	3165	B
	2019	2416	A	3533	B	580	A	3866	B
Effect		P-value							
Grain Crop		**< 0.001**		**0.0208**		**< 0.001**		**0.0051**	
Intercrop		0.2533		0.6854		NA		**0.0017**	
Year		**< 0.001**		**< 0.001**		**< 0.001**		**< 0.001**	
Grain Crop x Intercrop		0.7529		0.8853		**NA**		0.1680	
Grain Crop x Year		**< 0.001**		**< 0.001**		**< 0.001**		**< 0.001**	
Intercrop x Year		0.0965		0.4079		NA		0.0416	
Crop x Intercrop x Year		0.8084		0.4954		NA		0.4971	

[1] Red clover biomass is not reported for plots that were not interseeded. Any red clover collected in those plots was considered a weed.
[2] Forage yields represent the sum of crop and red clover biomass.

Grain yields for the corn-soybean-spelt rotation used in economic and environmental sustainability analyses averaged 10755 kg corn ha^{-1}, 2625 kg soybean ha^{-1}, and 2535 kg spelt ha^{-1} across two full three-year rotations (Caldwell et al., 2014). This corn yield is much higher than the New York State average yield of 6923 kg ha^{-1} for organic corn in 2019 (National Agricultural Statistics Service, 2020a). These soybean and spelt yields are closer to New York State averages of 2177 kg ha^{-1} for organic soybean, and 2793 kg ha^{-1} for organic spelt in 2019 (National Agricultural Statistics Service, 2020a).

The break-even price for Kernza grain was \$0.53 kg^{-1} when grown with interseeded red clover and \$0.64 kg^{-1} when grown in monoculture (Appendix B, Tables B1 & B2), assuming straw could be sold at the statewide average for organic straw in New York (National Agricultural Statistics Service, 2020a). Organic Kernza grain sold at\$0.53 kg^{-1} would represent a price premium 23% higher than the current price of \$0.43 kg^{-1} for organic winter wheat in New York. Kernza interseeded with red clover had a lower break-even grain price due to greater hay production than Kernza in monoculture despite higher costs incurred for additional field operations and clover seed (Table 9). Grain prices required for net returns of Kernza production to match the organic corn-soybean-spelt rotation were \$1.23 kg^{-1} with red clover and \$1.32 kg^{-1} in monoculture.

Table 9: Summary of enterprise budget analysis for three-year rotations for five organic cropping systems: Kernza intercropped with red clover (KC), Kernza with no clover (KN), annual winter wheat with (WC) and without red clover (WN), and a corn-soybean-spelt (CSS). All values are in USD and represent net present value of annual revenues, production costs, and income averaged over the three-year period and discounted 5% annually. Tables A1-A5 represent full enterprise budgets for each system.

	KC	KN	WC	WN	CSS
Crop revenues	------------------------	------------------------	USD ha^{-1}	------------------------	------------------------
Grain[1]	758.74	837.87	1289.17	1129.65	1581.96
Straw/hay	1054.71	822.04	609.96	559.78	-
Subtotal	1813.44	1659.91	1899.12	1689.43	1581.96
Production costs					
Field operations	290.16	259.51	345.85	339.11	360.71
Seed	189.67	74.09	292.58	126.33	193.93
Fertilizer	679.29	679.29	679.29	679.29	384.00
Land rental	148.60	148.60	148.60	148.60	148.60
Organic certification	7.05	7.05	7.05	7.05	7.05
Opportunity cost (5%)	65.74	58.43	73.67	65.02	54.72
Subtotal	1380.51	1226.98	1547.05	1365.41	1149.03
Net return[2]	432.93	432.93	352.07	324.03	432.93

[1] Kernza grain prices were calculated to match net income of the corn-soybean-spelt system as it had the highest net return of the three non-Kernza systems.
[2] Net returns of both Kernza systems and the corn-soybean-spelt system are equal due to the method used to calculate Kernza grain prices.

Sensitivity analysis was conducted to assess Kernza grain prices necessary to match net returns from the corn-soybean-spelt and wheat systems. Varying scenarios for Kernza grain and forage yields were developed based on a range of published values (Culman et al., 2013; Hunter et al., 2020a, 2020b; Jungers et al., 2017; Pugliese et al., 2019) then used to calculate grain prices if all costs and straw/hay prices were held constant (Table 10). Kernza grain prices ranged from \$9.56 kg^{-1} for the lowest yields observed during the first on-farm Kernza production trials in New York (Wayman et al., 2021), to \$0.10 kg^{-1} if both grain and forage yields were consistently at the highest values reported in current literature (Culman et al., 2013). Kernza grain prices ranged between -\$1.44 kg^{-1} and \$1.73 kg^{-1} under varying scenarios for wheat grain and straw prices (Table 11). Negative Kernza grain prices represented scenarios where the value of IWG forage was higher than the NPV of dual-purpose organic winter wheat, which occurred when wheat grain price was low and straw/hay prices were high. These estimates rely on relatively high market prices for organic grain, straw, and hay in the Northeast United States.

Table 10: Sensitivity analysis of the effect of Kernza grain and forage yields on Kernza grain price required to match returns from an organic corn-soybean-spelt rotation. Kernza yields are based on low and high values observed in field trials in New York and other published studies.

Kernza Forage Yield kg ha^{-1}	**Kernza Grain Yield**							
	---------- kg ha^{-1} ----------							
	140[1]	250	500	620[2]	750	1000	1250	1500[3]
	Kernza Grain Price							
	---------- USD kg^{-1} ----------							
3250[1]	9.56	5.36	2.68	2.16	1.68	1.34	1.07	0.89
5000	7.97	4.46	2.24	1.80	1.38	1.12	0.89	0.74
6100[2]	6.96	3.90	1.96	1.58	1.20	0.98	0.78	0.65
7500	5.69	3.18	1.60	1.29	0.96	0.80	0.65	0.53
10000	3.41	1.91	0.96	0.77	0.53	0.48	0.38	0.32
12500[3]	1.13	0.63	0.32	0.26	0.11	0.16	0.12	0.10

[1] Low values from on-farm trials conducted with local organic grain farmers between 2016 and 2019 (Wayman et al., 2021)

[2] Approximate mean annual yields reported in this study

[3] Highest published values for organic Kernza production (Culman et al. 2013)

Table 11: Sensitivity analysis of Kernza grain price calculated to match NPV of dual-purpose organic winter wheat under varying wheat grain and straw price scenarios. Calculations assume that Kernza hay price is equal to wheat straw price to reflect the strength of the local market for animal feed and bedding. Wheat grain and straw prices represent highs and lows observed in state- and national-level USDA conventional and organic crop production surveys, see footnotes for sources.

Straw Price	**Wheat Grain Price**				
USD kg^{-1}	---------------------- USD kg^{-1} ---------------------				
	0.15[1]	0.20	0.25	0.35	0.43[2]
	Kernza Grain Price				
	---------------------- USD kg^{-1} ----------------------				
0.00[3]	0.36	0.61	0.85	1.34	1.73
0.04	0.27	0.51	0.89	1.24	1.63
0.10	-0.02[4]	0.23	0.60	0.95	1.35
0.15	-0.29	-0.04	0.20	0.69	1.08
0.20	-0.49	-0.27	0.00	0.48	0.88
0.30	-0.96	-0.72	-0.48	0.01	0.40
0.40[5]	-1.44	-1.19	-0.96	-0.47	-0.07

[1] Approximate national average for conventional winter wheat (National Agricultural Statistics Service, 2020b)
[2] Approximate New York State average for organic winter wheat (National Agricultural Statistics Service, 2020a)
[3] Represents systems where straw is not harvested or there are no markets. Costs for straw harvest were not included in calculations.
[4] Negative Kernza grain prices represent scenarios where the value of Kernza straw alone is higher than the NPV of wheat production
[5] Highest observed wheat straw price ($360/ton) at Pennsylvania hay and forage auctions in 2019

At the fair quality organic hay price of \$135 ton^{-1} (\$122.50 Mg^{-1}) used as the current market benchmark in this study, approximately half of IWG cropping system revenue is derived from grain sales and half from hay sales (Table 9). Organic grains often receive price premiums of 100% or more over conventional grains, while organic forages may only receive a 30-50% premium (Wieme et al., 2020). This discrepancy will make it more difficult for IWG to compete economically with organic grain crops, as IWG's lower grain yields are further penalized while its high forage production is not rewarded. On the other hand, New York was the state with the highest tonnage and value of-farm sales of organic grass (non-alfalfa) hays during the most recent national survey in 2019 (National Agricultural Statistics Service, 2020a). Over 60,000 tons of grass hays were sold by New York farmers in 2019 for a total of \$8M USD, representing 21.5% of organic grass hay sales in the US. This high-value market for forages, relatively low cost of land, and potential for integrated crop-livestock systems in dairy-producing Northeastern states creates an ideal situation for introducing a dual-purpose grain and forage crop like IWG. In comparison to an economic analysis of IWG forage production in Minnesota where the NPV of IWG straw alone was frequently higher than production costs for both grain and forage (Hunter et al., 2020b), hay prices were higher and land costs lower in our study. The economic prospects of dual-purpose IWG production could be further improved by harvesting higher quality hay in the spring or fall. This strategy has been found to increase total crop biomass and not affect grain yield potential the following growing season relative to a control where IWG forage was not harvested (Pugliese et al., 2019).

Changes in the yield or price of either co-product could also alter economic outcomes considerably. For example, if an IWG stand consistently produced 1000 kg grain ha^{-1} yr^{-1} and 10000 kg hay ha^{-1} yr^{-1} for three years, the grain price required to match NPV of the most profitable corn-soybean-spelt system would be \$0.48 kg^{-1} (Table 10). This would represent a more modest price premium of 12% compared with organic winter wheat.

It is also noteworthy that the spelt year of the corn-soybean spelt system had a net negative cash flow (Appendix B, Table B5), a loss that is justified by organic farmers in light of the other services provided by the spelt. Specifically, at the field level added crop diversity disrupts pest and pathogen populations and allows for an interseeded clover crop to increase soil nitrogen availability for the following, higher value corn crop (Caldwell et al., 2014). At the whole-farm level, crop diversification is known to increase resilience to variable weather patterns (Gaudin et al., 2015) and provides additional flexibility in farm management by distributing field operations like planting and harvesting across a longer period of the growing season (Bell et al., 2008). Kernza may provide similar benefits in rotation with other crops, and thus there is the possibility that farmers would be willing to grow Kernza for lower grain and forage prices than what is calculated here. This is supported by early adopters of Kernza, who acknowledge that Kernza may be at a disadvantage to other crops if the farm's only goal is short term profit, but that they are also motivated by assuring a "balance" of economic, management, and environmental goals across their farm in the longer term (Lanker et al., 2020).

In our study poultry litter represented about half of all production costs in the IWG systems at \$679 ha^{-1} yr^{-1} (Table 9). In New York State poultry litter costs approximately 13 times more per kg N than synthetic fertilizers, which can inflate the production costs of organic crops (Cox et al., 2019). Use of less-processed and locally available animal manures, especially those produced on-farm in integrated crop-livestock systems, could drastically decrease this cost but may result in less precise levels of N application and possible overapplication of P. In a study evaluating a conventional South Carolina corn-soybean-wheat rotation, using solely poultry litter for crop fertilization resulted in higher NPV than synthetic fertilizers when litter was freely available on-farm and the only associated cost was handling and spreading, but this advantage disappeared when poultry litter needed to be purchased for ~\$150 ha^{-1} (Adigun, 2020). Nitrogen fixation by intercropped legumes can also potentially reduce fertilizer costs in IWG production systems (Li et al., 2021; Tautges et al., 2018), but managing IWG-legume mixtures requires further research for various desired outcomes (e.g., maximizing grain or forage production, minimizing energy use or GHG emissions, improving soil health) to be optimized.

2.4.4 Energy analysis

Total energy use ranged between 6220 MJ ha^{-1} yr^{-1} for the Kernza monoculture to 8050 MJ ha^{-1} yr^{-1} for the winter wheat intercropped with red clover (Figure 4). Diesel fuel and poultry litter were the highest energy inputs for all systems, but the relative importance of these two inputs differed between the corn-soybean-spelt system and the four systems from the perennial/annual comparison experiment (Figure 4). The corn-soybean-spelt system, despite being considered a “high fertility” system, used 44% less poultry litter as fertilizer than the other systems due to nitrogen credits from soybean and clover. On the other hand, the corn-soybean-spelt system used 27% more diesel than the IWG monoculture system that had the lowest fuel use, due to additional cultivation operations to manage weeds during the corn and soybean years of the rotation. Only minor differences were observed in energy used for the fewer field operations in the perennial IWG systems compared with the annual wheat systems, but differences in crop and clover seed energy were substantial.

The highest energy use value estimated was 8050 MJ ha^{-1} yr^{-1} for the wheat-clover intercrop, which is considerably less than the lowest energy use of 9217 MJ ha^{-1} yr^{-1} for a six-year organic crop rotation calculated using the same FEAT model (Hoffman et al., 2018). The main difference between the organic cropping systems reported in Hoffman et al. (2018) and our study was the number of field operations for seedbed preparation and weed management. For example, Hoffman et al. (2018) included a total of seven additional disking and cultivation operations across their three-year corn-soybean-wheat rotation representing a difference of 1907 MJ ha^{-1} yr^{-1} compared with the corn-soybean-spelt system analyzed in this study. These energy use values are also lower than the United States national average of 8725 MJ ha^{-1} yr^{-1} for conventional wheat production (Piringer and Steinberg, 2006).

The method of allocation had a large impact on relative energy use of the five cropping systems, with IWG having the largest differences between allocation methods (Figure 4). When IWG was intercropped with red clover it had the lowest energy use per kg of harvested biomass inclusive of grain and forages, the third highest energy use per hectare, and by far the highest energy use per kg grain. Allocated per kg dry biomass harvested, Kernza intercropped with red clover required only 0.85 MJ kg^{-1} yr^{-1}, while the corn-soybean-spelt system required 1.45 MJ kg^{-1} yr^{-1} as crop residues were not harvested in that system. In contrast, when allocated per kg of grain yield corrected to market moisture levels, the corn-soybean-spelt system required 1.09 MJ kg^{-1} yr^{-1} and the Kernza-red clover system required 10.80 MJ kg^{-1} yr-

^{1}, a striking ten-fold difference in energy use if grain is the sole output of the production system. These differences are clearly driven by the low grain yields and high forage production of IWG, again highlighting the importance of dual-purpose use of the IWG crop.

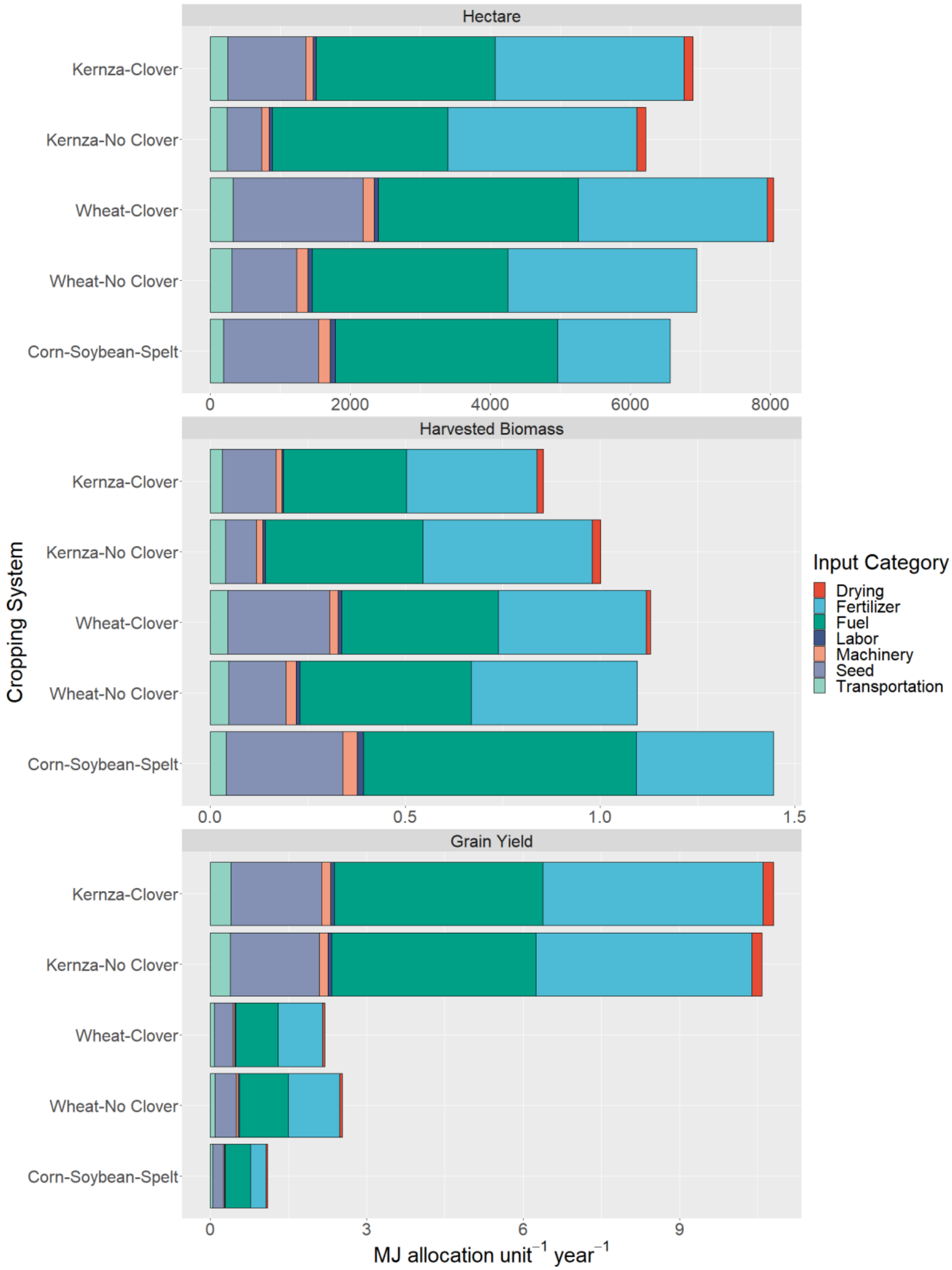

Figure 4: Crop production energy use comparison for five organic cropping systems. Scale of x-axis units varies by the three methods of allocating energy to production: Unit of area basis (MJ ha^{-1} yr^{-1}), Unit of crop biomass harvested basis (MJ kg crop biomass^{-1} yr^{-1}), and Unit of grain yield basis (MJ kg grain yield^{-1} yr^{-1}).

2.4.5 Greenhouse gas emissions

Total greenhouse gas emissions followed the same pattern as energy use, ranging from 963 kg CO_2e ha^{-1} yr^{-1} for Kernza monoculture to 1106 kg CO_2e ha^{-1} yr^{-1} for wheat intercropped with red clover (Figure 5). Emissions were dominated by direct emissions N_2O from fertilizer applications, followed by direct emissions from fossil fuel combustion. Indirect emissions from poultry litter and seed production, also contributed considerably to the totals for all systems. Crop residue decomposition was an important source of N_2O emissions in the corn-soybean-wheat system, but not for the dual-purpose IWG and wheat systems where it was estimated that 90% of aboveground crop residues were harvested for hay or straw. This difference is due to the choice of system boundaries, as the N of crop residues does not disappear after they are harvested, so emissions related to those products are externalized from the systems. Kernza intercropped with red clover has the lowest emissions per kg crop biomass harvested (0.12 kg CO_2e kg^{-1} yr^{-1}) and the highest emissions per kg grain yield (1.56 kg CO_2e kg^{-1} yr^{-1}), while the corn-soybean-spelt system again exhibited the opposite trend (0.23 kg CO_2e kg^{-1} yr^{-1} with crop biomass allocation; 0.20 kg CO_2e kg^{-1} yr^{-1} with grain yield allocation). Full tables of inputs and calculated energy use and greenhouse gas emissions are included in the supplementary materials (Appendix B, Tables B6-B10).

Greenhouse gas emission estimates reported from this study are less than half the emissions estimated by Hoffman et al. (2018) for organic cropping systems in the northeastern United States, partly due to fewer field operations but also because of differences in emissions from crop residues. It appears that GHG estimates calculated using the FEAT model are sensitive to how crop residue management is parameterized, a factor that should be considered by others using the model to evaluate the sustainability of cropping systems. Emissions from the wheat systems (0.353 – 0.381 kg CO_2e kg grain^{-1} yr^{-1}) were similar to emissions of 0.4 kg CO_2e kg grain^{-1} for wheat production in The Netherlands (Kramer et al., 1999) and Australia (Biswas et al., 2010), suggesting that values calculated in this study are reasonable estimates.

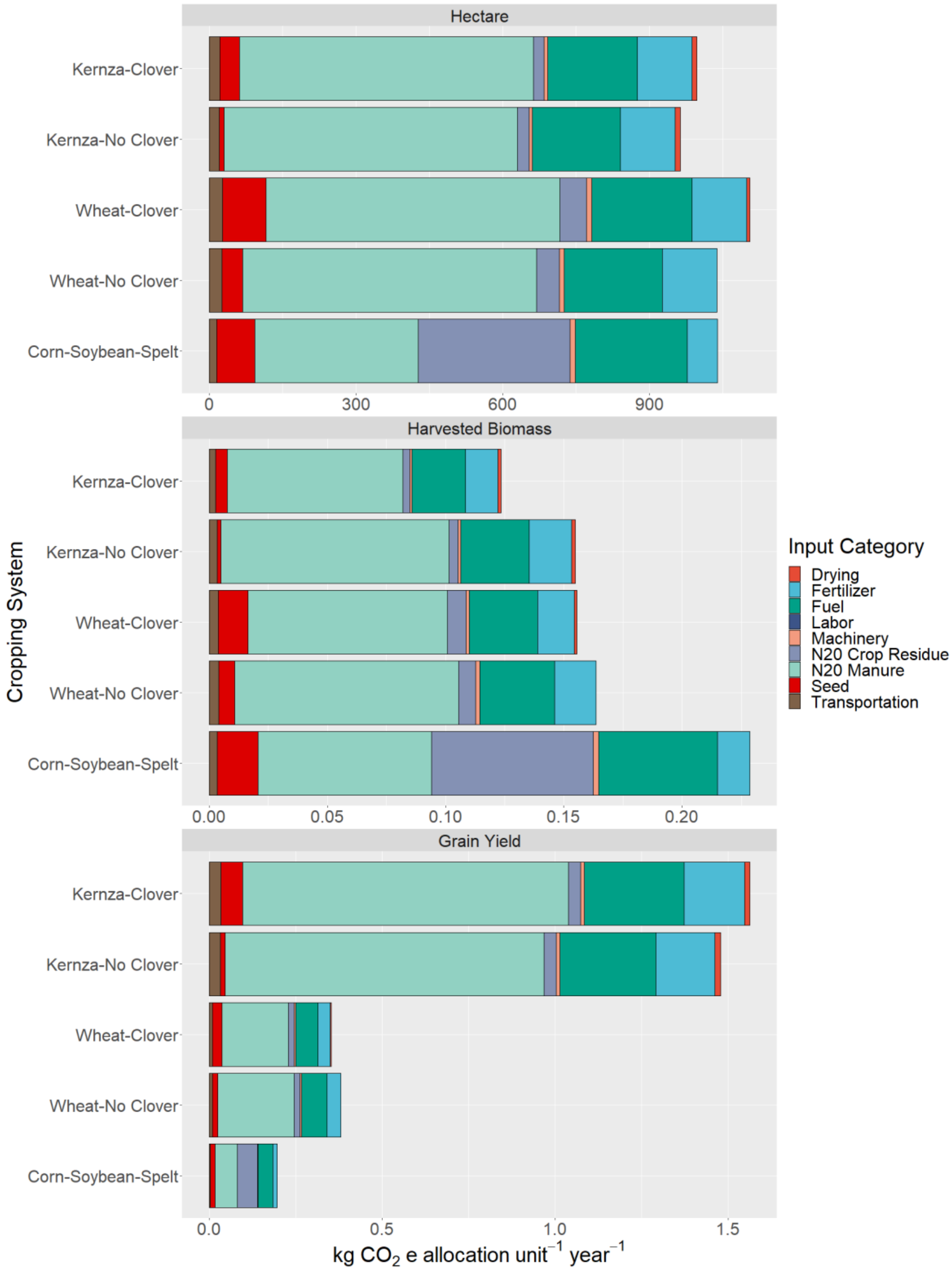

Figure 5: Greenhouse gas emissions comparison for five organic cropping systems. Scale of x-axis units varies by the three methods of allocating emissions to production: Unit of area basis (kg CO_2e ha^{-1} yr^{-1}), Unit of crop biomass harvested basis (kg CO_2e kg crop $biomass^{-1}$ ha^{-1} yr^{-1}), and Unit of grain yield basis (kg CO_2e kg grain $yield^{-1}$ ha^{-1} yr^{-1}).

2.4.6 Emergy evaluation

Emergy-based sustainability indicators for grain and forage production show that all five systems have relatively low environmental impact due to their high reliance on renewable resources and low amounts of external inputs. The chemical energy of rain was the dominant emergy flow in all systems, followed by the emergy of organic fertilizers and in the annual systems, soil erosion (Figure 6). Specific emergies for grain were highest in Kernza systems and lowest in the corn-soybean-spelt system due to differences in grain yields (Table 12). An opposite trend was observed in specific emergies of straw or hay, with Kernza systems having lower values than wheat systems (Table 13). Crop residues were not harvested in the corn-soybean-spelt system. The perennial Kernza systems had higher EYR than the wheat systems, and lower ELR than all three annual systems, however, due to fewer field operations and lower estimated soil erosion (Tables 12 and 13). The ESI of the two Kernza systems was approximately two-to-three times higher than any of the annual systems due to the higher relative contribution of renewable inputs to Kernza production (Tables 12 and 13). Full emergy tables for each cropping system are included in the supplementary materials (Appendix B, Tables B11-B15).

Table 12: Summary results of emergy evaluation of three years of organic grain production from five cropping systems: Kernza intercropped with red clover (KC), Kernza with no clover (KN), annual winter wheat with (C) and without red clover (WN), and a corn-soybean-spelt rotation (CSS). Emergy-based sustainability indicators include Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI).

Sustainability indicator	**KC**	**KN**	**WC**	**WN**	**CSS**
Specific emergy (seJ g^{-1})	3.67E+09	3.50E+09	1.09E+09	1.24E+09	5.82E+08
Emergy yield (Y)	7.03E+15	6.84E+15	1.03E+16	1.02E+16	9.30E+15
Renewable fraction (R)	4.70E+15	4.70E+15	4.70E+15	4.70E+15	4.70E+15
Nonrenewable local fraction (N)	7.62E+14	7.62E+14	2.82E+15	2.82E+15	2.82E+15
Purchased fraction (F)	1.56E+15	1.40E+15	2.74E+15	2.64E+15	1.78E+15
EYR (Y/F)	4.50	4.88	3.74	3.84	5.23
ELR (N+F/R)	0.49	0.46	1.18	1.16	0.98
ESI (EYR/ELR)	9.11	10.60	3.17	3.31	5.36

Table 13: Summary results of emergy evaluation of three years of organic straw or hay production from four cropping systems: Kernza intercropped with red clover (KC), Kernza with no clover (KN), and annual winter wheat with (WC) and without intercropped red clover (WN). Emergy-based sustainability indicators include Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI).

Sustainability indicator	**KC**	**KN**	**WC**	**WN**
Specific emergy (seJ g^{-1})	3.16E+08	3.90E+08	7.78E+08	8.44E+08
Emergy yield (Y)	7.14E+15	6.87E+15	1.03E+16	1.02E+16
Renewable fraction (R)	4.70E+15	4.70E+15	4.70E+15	4.70E+15
Nonrenewable local fraction (N)	7.62E+14	7.62E+14	2.82E+15	2.82E+15
Purchased fraction (F)	1.64E+15	1.40E+15	2.75E+15	2.65E+15
EYR (Y/F)	4.37	4.90	3.74	3.84
ELR (N+F/R)	0.51	0.46	1.18	1.16
ESI (EYR/ELR)	8.56	10.65	3.16	3.30

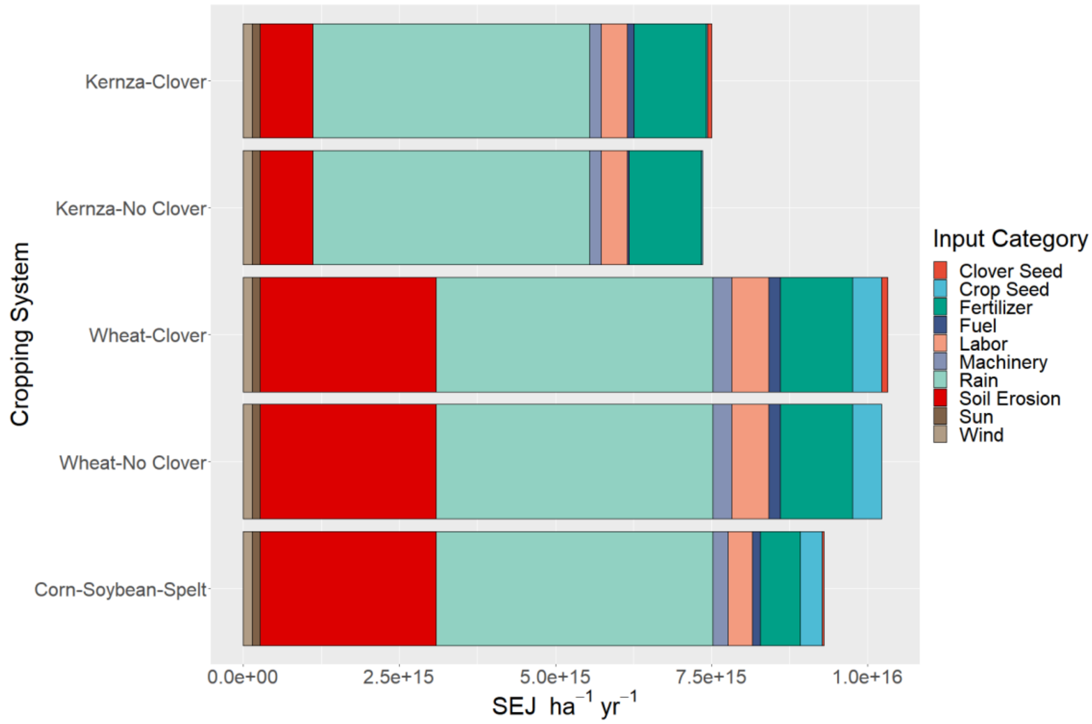

Figure 6: Emergy flows of inputs to five organic cropping systems.

Emergy is particularly appropriate for evaluating agricultural systems because they are at their core systems that utilize higher quality, more concentrated forms of energy obtained from the economy to harvest lower quality, but renewable, energy from the sun, wind, and rain in the form of crop products (Martin et al., 2006). The perennial IWG systems utilize a higher proportion of renewable resources relative to non-renewable resources of soil erosion and purchased inputs than annual grain cropping systems, resulting in ESI values that were three times higher for IWG (ESI = 8.33 – 10.39) than annual wheat (ESI = 3.16 – 3.31). The high emergy value of rainwater relative to other inputs had a strong impact on the sustainability of all five systems evaluated in this study (Figure 6). Agricultural systems that depend on groundwater extraction for crop irrigation can be much less sustainable from an emergy perspective. For example, an evaluation of wheat production in an arid region of China found an ELR of 10.59 and ESI of 0.11, indicating much higher environmental stress and lower overall sustainability than the systems in our study, due to use of groundwater at rates higher than natural recharge and the high emergy cost of electricity required for pump operation (Wang et al., 2014).

Emergy evaluation also values the embodied energy of some inputs, such as machinery and labor, higher than simple energy analysis because emergy conversions account for not only the energy of producing a machine or performing a task, but also the energy embodied in the raw materials, information, and environmental processes necessary to create a machine or raise, educate a laborer, or generate a centimeter of topsoil (Brown et al., 2000). This also contributed to better sustainability indicators for the IWG system, which greatly reduces soil erosion and utilizes less labor and machinery for field operations after the first growing season because there is no need to till the soil and replant the crop.

The five organic grain cropping systems evaluated in this study also performed well relative to other agricultural systems evaluated using emergy indicators. The emergy yields of IWG (7.11E+15 seJ ha^{-1} yr^{-1}), wheat (1.03E+16 seJ ha^{-1} yr^{-1}), and corn-soybean-spelt (9.30E+15 seJ ha^{-1} yr^{-1}) systems were higher than a conventional silage corn production system in the Netherlands (1.91E+15 seJ ha^{-1} yr^{-1}; Ghaley et al., 2018), but lower than a conventional grain corn production system in Kansas, USA (1.30E+16 seJ ha^{-1} yr^{-1}; Martin et al., 2006) and the aforementioned wheat production system in China (2.00E+16 seJ ha^{-1} yr^{-1}; Wang et al., 2014). The ESIs of IWG grain (8.90 – 10.34) and forage (8.33 – 10.39) production were much higher than any of these conventional grain production systems. Comparisons of ELRs between conventional and organic wheat production have revealed that organic systems create two-to-three times less environmental stress (Coppola et al., 2008; Kuczuk, 2016), and based on our analysis, perennial systems could further reduce the impact of organic grain and forage production.

2.4.7 Comparison of sustainability indicators between systems

Comparison of sustainability indicators between systems

Normalizing all sustainability indicators to the corn-soybean-spelt system that is typical of organic grain production in New York State provides a relative comparison of all five systems (Figure 7). The corn-soybean-spelt system produced the most grain by far due to the high yield of corn, but less total biomass was harvested from that system than was harvested from the dual-purpose IWG and wheat systems. These differences in co-products can have a large effect on the interpretation of sustainability indicators depending on allocation method, as is seen in the comparisons of energy use and GHG emissions above. On a per hectare basis, the IWG-red clover and both wheat systems used slightly more energy than the corn-soybean-spelt system, but the IWG monoculture used slightly less. Greenhouse gas emissions from both IWG systems and the wheat monoculture were lower than the corn-soybean-spelt system, while emissions from the wheat-red clover system were slightly higher. Both perennial IWG systems performed better than all of the annual systems for the Emergy Sustainability Index due to a higher relative reliance on renewable natural resources. Production costs were higher for IWG and wheat systems than the corn-soybean-spelt system due to higher inputs of poultry manure. Kernza grain yields would need to increase substantially or command a price premium approximately three times that of organic winter wheat, to have similar net returns to the corn-soybean-spelt system over a three-year rotation.

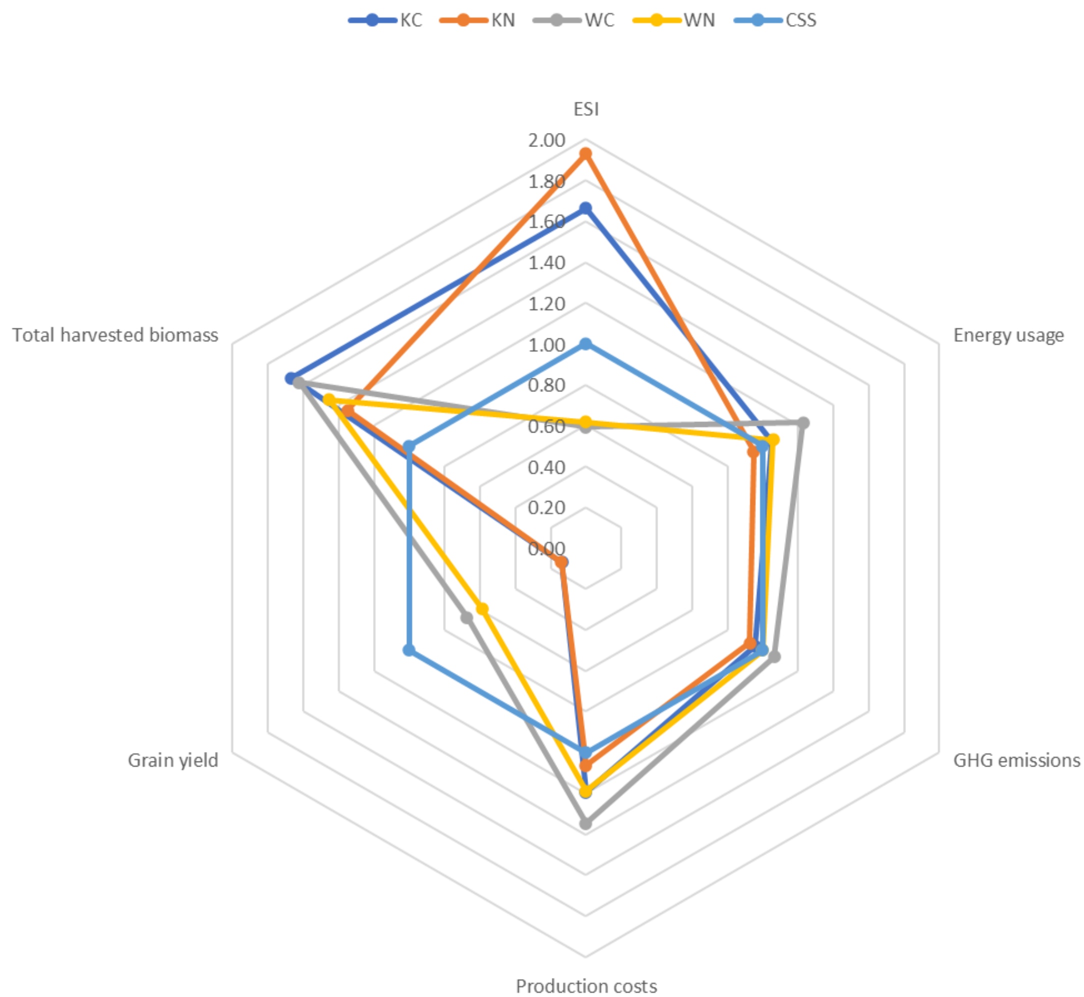

Figure 7: Comparison of five organic cropping systems across agronomic, economic, and environmental sustainability indicators: Grain yield (kg ha^{-1} yr^{-1}), total harvested biomass (kg ha^{-1} yr^{-1}), Emergy Sustainability Index (ESI, unitless), energy use (MJ ha^{-1} yr^{-1}), greenhouse gas emissions (kg CO_2e ha^{-1} yr^{-1}), and total production costs (USD ha^{-1} yr^{-1}). Cropping systems evaluated were Kernza-red clover intercrop (KC), Kernza monoculture (KN), wheat-red clover intercrop (WC), wheat monoculture (WN), and corn-soybean-spelt rotation (CSS).

2.4.8 Implications for incorporating Intermediate wheatgrass into sustainable cropping systems

The results of this study are highly dependent on the economic value of harvesting Kernza biomass for use as a fair-quality hay after grain harvest. Crop residue removal has mixed impacts on crop productivity and indicators of annual cropping system sustainability (Battaglia et al., 2021). Indicators of soil health are sensitive to site-specific factors including soil depth and texture, slope, and tillage practices, but generally negative impacts of residue removal on soil erosion and nutrient leaching are reduced when residue removal is below 30%. In contrast, on-farm GHG emissions are lowest when all residues are removed, but this does not account for any emissions from residues being used for animal feed, biofuel production, or other uses after harvest (Battaglia et al., 2021). Kernza systems may be able to realize many of the benefits of residue removal without the drawbacks. Removal of Kernza straw after harvest has neutral or positive impacts on grain yield in subsequent years (Hunter et al., 2020a; Pugliese et al., 2019), and soil erosion and nutrient leaching are both much lower in Kernza production systems than in comparable annual grains even when crop residues are harvested (Culman et al., 2013; Jungers et al., 2019). As the economic value of Kernza hay and straw is a critical component of the economic viability of the crop as shown in this study and another recent evaluation of Kernza profitability (Hunter et al., 2020b), using Kernza as a dual-purpose crop for grain and forage production appears to be a win-win-win proposition.

The boundaries and assumptions that were made when defining the limits of the systems being analyzed have significant impacts on the assessment. The decisions to treat grain and forages as commodities and to apply fertilizers at the same rate regardless of intercropping treatment reduced some possible advantages of the IWG-red clover cropping system from an economic utility standpoint. The benefits of growing Kernza as a dual-purpose crop could be further enhanced on farms where mixed Kernza-clover forages could be used for animal feed. Integrating crop and livestock production is an important principle of sustainable agriculture because it minimizes externalities at the farm scale (Davis et al., 2012). The use of Kernza as a dual-purpose crop producing both grain and animal feed and the incorporation of forage legumes into field crop production would both help close material and energy loops. In such a system the recycling of nutrients by using animal manures as fertilizer would also reduce the need for external inputs, thereby further reducing environmental impact and increasing profitability. This type of farm-agroecosystem circularity can also increase stability and resilience at the whole-farm scale (Hercher-Pasteur et al., 2021).

Incorporating a perennial grain crop like Kernza into organic crop rotations in the Northeast United States could also provide indirect benefits to farm management that are not quantified in this study. Analysis of perennial wheat cropping systems in Australia revealed direct and indirect benefits to farmers (Bell et al., 2008). Direct benefits of perennial small grains include reduced external inputs and opportunities for grazing livestock in dual-use systems, while indirect benefits to whole-farm management include more flexibility in equipment usage and labor throughout the year and in decision making about crop management based on environmental and economic factors, such as prioritizing forage production when low water availability reduces grain yield or when animal feed prices are high.

2.4.9 Conclusion

Organic perennial IWG cropping systems perform as well or better than annual cropping systems for several measures of environmental sustainability, especially when grain and forages are valued as co-products of the system. Soil health indicators measured in the top 20 cm of the profile improved for both IWG and annual wheat systems over three years, although indicators may be improving faster for IWG systems. Thus, differences may become more apparent in longer-term studies. The energy use and GHG emissions for IWG production were relatively low when calculated per hectare or per kg of harvested biomass due to lower inputs of seed, fuel, and machinery and high forage biomass production, but performed poorly for these indicators when only grain was considered as a product of the system. Sustainability indicators based on emergy, which accounts for the energy harvested from renewable natural resources, show that the IWG systems create less environmental stress and generate more emergy per unit of external input than annual grain production systems. These environmental benefits do have tradeoffs with economic performance of the IWG systems, however, as low grain yields from IWG would require substantial price premiums to produce net returns equivalent to comparable organic grain rotations. Several factors could improve the economic sustainability of IWG production in New York State and other Northeastern U.S. states, including improving grain and forage yields through breeding programs and agronomic best management practices, incorporating livestock grazing or additional forage harvests, or compensating farmers for the ecosystem services provided by perennial cropping systems.

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CHAPTER 3

STRIP-TILLAGE RENOVATION OF INTERMEDIATE WHEATGRASS (*THINOPYRUM INTERMEDIUM*) FOR MAINTAINING GRAIN YIELD IN MATURE STANDS

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3.1 Abstract

Kernza® intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & Dewey], the first perennial grain crop to come to market in North America, can provide a number of ecosystem services when integrated into cropping systems that are dominated by annual grain crops. However, grain yield from Kernza is lower than comparable annual cereal crops such as wheat and oats. Also, although Kernza is a long-lived perennial that can persist for decades, grain yield tends to decline over time as Kernza stands age leading most farmers to replant or rotate to a different crop after three to five years. Increased intraspecific competition as stand density increases with age has been reported to cause grain yield declines. We investigated the effect of strip-tillage applied at two different timings, between the third and fourth grain harvests, from a Kernza stand in upstate New York. Strip-tillage applied in late fall as plants were entering dormancy increased grain yield by 61% when compared to the control

treatment without strip-tillage. However, total crop biomass was not reduced resulting in a greater harvest index for the fall strip-tillage treatment. Strip-tillage applied before stem elongation the following spring reduced overall tiller density and total crop biomass but did not impact tiller fertility or grain yield compared to the control treatment without strip-tillage. Increased grain yield in the fall strip-tillage treatment was due to an increase in the percentage of tillers that produced mature seedheads. This suggests that grain yield decline over time is at least partially caused by competition between tillers in dense stands. Results support further research and development of strip-tillage and other forms of managed disturbance as tools for maintaining Kernza grain yield over time.

3.2 Introduction

Perennial grain crops have the potential to produce staple foods and forage for livestock while mitigating many of the environmental externalities of annual grain production (Crews et al., 2018; Pimentel et al., 2012). Kernza® is a variety of intermediate wheatgrass (*Thinopyrum intermedium* Barkworth & Dewey) bred for grain production by researchers at The Land Institute, Salina, Kansas, USA (DeHaan et al., 2018). Intermediate wheatgrass is a rhizomatous perennial grass native to the Caucasus region of Eurasia that has historically been used as a forage crop due to its high biomass production and good forage quality (Hendrickson et al., 2005; Vogel and Jensen, 2001). Intermediate wheatgrass was selected for domestication as a perennial grain crop because of its relatively large seed size, favorable agronomic characteristics (i.e. lower shattering, more uniform height, more synchronous maturation), and better flavor profile than other candidate perennial grasses (Wagoner, 1990).

Increasing crop diversity in agroecosystems can restore ecosystem services and improve production efficiency (Asbjornsen et al., 2014). This approach is viewed as an important component of broader changes to food systems that are necessary to ensure global nutritional security while maintaining or enhancing the natural capital that sustains agricultural production (Foley et al., 2005). Development of intermediate wheatgrass as a perennial grain crop is largely motivated by its ability to contribute ecosystem services including enhanced soil health and water quality (Culman et al., 2013; Jungers et al., 2019), and the potential for soil carbon storage to mitigate anthropogenic climate change (Pugliese et al., 2019; Sprunger et al., 2019, 2018b). These characteristics have also motivated food industries to develop products that incorporate Kernza as part of their corporate sustainability strategy (Karnowski, 2017; Lubofsky, 2016).

Despite advances in the development of Kernza as a perennial grain crop, low grain yields compared to annual small grains continue to be a potential barrier to adoption (Hunter et al., 2020a). While adoption may not be wholly dependent on economic returns for farmers motivated by innovation and environmental benefits, crop productivity and profit margins are major factors in farmer decision-making (Lanker et al., 2020; Marquardt et al., 2016; Wayman et al., 2019). Currently, Kernza grain yields range between 500 and 1700 kg ha^{-1} at first harvest and then decline in subsequent years (Culman et al., 2013; Dick et al., 2018; Hunter et al., 2020a; Jungers et al., 2017; Pugliese et al., 2019). Farmers report that developing crop management techniques that maintain yields over time is a top priority for research (Lanker et al., 2020). Management interventions to improve grain yield in young stands and maintain yield as stands age have included crop defoliation after harvest, either by mowing (Hunter et al., 2020a; Pugliese et al., 2019) or grazing (Dick et al., 2018), intercropping with legumes (Favre et al., 2019; Tautges et al., 2018), and increasing row spacing (Hunter et al., 2020a). These efforts have had mixed results, with most showing yield benefits for the first few harvests but little progress towards sustaining yields in more mature stands. A recent study by Bergquist (2020) examined the use of banded herbicide applications, inter-row cultivation, inter-row burning, and mowing to manage a Kernza stand in its third and fourth years of growth. Inter-row cultivation during the fall and herbicide applications during the spring after the second and third harvests resulted in the highest grain yields at the fourth harvest, but these yields were not statistically different from the control treatment.

Based on observations from previously cited research on Kernza stand management, it is likely that yield decline in Kernza stands over time is at least partially due to intraspecific competition that causes reduced seed production. Possible mechanisms for yield declines include a) density-dependent interactions in the rhizosphere that decrease resource allocation to seed production (Tautges et al., 2018), b) changes in light quality at the crown that reduce reproductive tiller initiation or trigger light avoidance syndrome (Jungers et al., 2017), and c) water or nutrient limitation during critical periods of growth and reproduction (Hunter et al., 2020b; Tautges et al., 2018). Alternatively, shifts in whole-plant resource allocation from competitive to stress-tolerant strategies as plants age (Jaikumar et al., 2016) may impose physiological limits on seed production in older stands, but stand-thinning could overcome these limits by stimulating new growth. These observations also suggest that yield declines with stand age are not caused by resource limitations across the entire stand, because total biomass production is generally maintained or increases from season to season, while harvest index declines.

Mechanical stand thinning can maintain seed yield over five harvests in intermediate wheatgrass forage varieties (Canode, 1965) and there have been calls for management research to focus on reducing intra-stand competition (Bergquist, 2020; Hunter et al., 2020a). Here we report on an experiment using deep, narrow strip-tillage to disturb the root zone of a Kernza stand at two different times between the third and fourth grain harvests: in late fall when plants are entering dormancy and in early spring prior to stem elongation. The objective of this research was to determine whether strip-tillage increases grain yield of Kernza at the subsequent harvest. We hypothesized that strip-tillage would reduce tiller density but would increase resource allocation to seed production, measured as harvest index. Total biomass production and yield components were also measured.

3.3 Methods

3.3.1 Experimental Design

This experiment was established in a field of Cycle 3 Kernza® intermediate wheatgrass from The Land Institute's breeding program, planted on August 26, 2014 at the Musgrave Research Farm in Aurora, New York, USA (42.7222 N, 76.6636 W). Field operations conducted between the field being planted and data collection are summarized in Table 14. Soil type at the site is Honeoye silt loam with a pH of 7.5 and 3.2% organic matter. Mean annual temperature was 9.1°C and mean annual precipitation was 918 mm for the most recent NOAA 30 year climate averages (1981-

2010), but annual temperatures tended to be higher and precipitation lower between 2014 when Kernza was planted and 2018 when the experiment was conducted (Figure 8). The field was planted at a seeding rate of 16.8 kg ha^{-1} in 19-cm rows using a John Deere No-Till Grain Drill model 1590. A tank mix of Harmony Extra SG (11.7 g ha^{-1} thifensulfuron-methyl and 5.8 g ha^{-1} tribenuron-methyl), Banvel (140.1 g ha^{-1} dimethylamine salt of dicamba), and Barrage (288.1 g ha^{-1} 2,4-D ester) was applied to the entire field on April 24, 2017 to manage an expanding population of Canada thistle [*Cirsium arvense* (L.) Scop.]. Grain was harvested and straw removed between late August or early September in 2015, 2016, and 2017.

Table 14: Field operation dates from Kernza planting in August 2014 to sampling in August 2018.

Date	**Field Operations**
8/16/2014	Field planted in 19 cm rows at 16.8 kg ha^{-1} seeding rate.
5/4/2015	Fertilizer applied to supply 74 kg N ha^{-1}.
9/15/2015	First grain harvest from the field.
10/1/2015	Straw is flail chopped to 10 cm height and removed from field.
5/9/2016	Fertilizer applied to supply 74 kg N ha^{-1}.
8/24/2016	Grain harvest and straw removal.
4/19/2017	Fertilizer applied to supply 74 kg N ha^{-1}.
4/24/2017	Harmony Extra SG, Banvel, and Barrage herbicides applied to manage *Cirsium arvense.*
8/28/2017	Grain harvest and straw removal.
10/20/2017	Fall strip-tillage treatment applied.
4/24/2018	Fertilizer applied to supply 74 kg N ha^{-1}.
5/9/2018	Spring strip-tillage treatment applied.
8/31/2018	Quadrat samples collected.

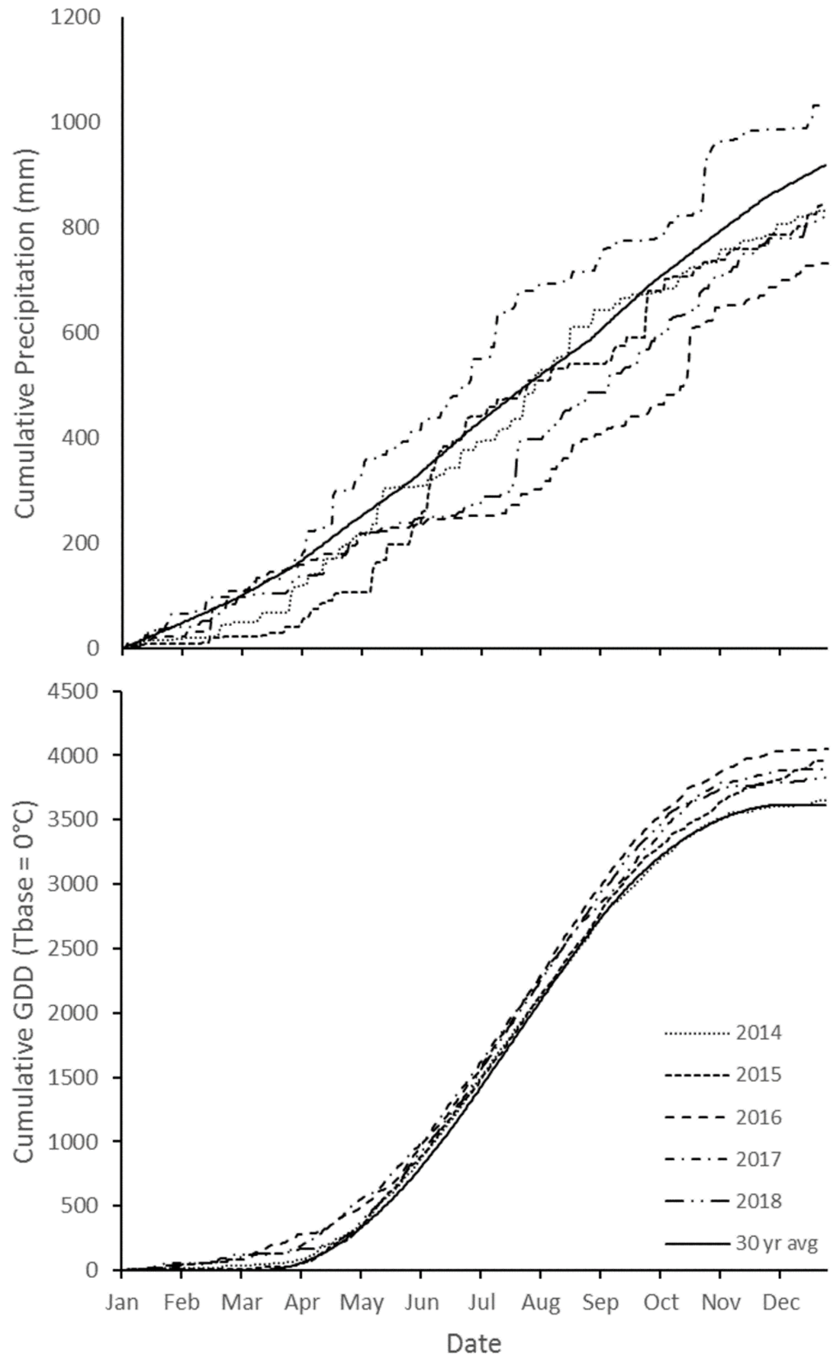

Figure 8: Cumulative growing degree days (Tbase = 0°C) and precipitation for each of the five years between Kernza planting in 2014 and the fourth grain harvest in 2018 reported in this study. The most recent NOAA 30-year climate averages (1981-2010) are included to provide context.

The experiment was set up as a randomized complete block design with three treatments replicated five times. Strip-tillage treatments were applied using an Unverferth Zone-Builder Subsoiler Model 122 (Figures 9 and 10). Treatments were: 1) strip-tillage on October 20, 2017 after substantial post-harvest regrowth ("fall strip-tillage"); 2) strip-tillage on May 9, 2018 after green-up but prior to stem elongation ("spring strip-tillage"), 3) and an untreated control that had not been tilled or cultivated since the field was planted ("control"). Plots measured 4.6 m wide by 24.4 m long. The entire field was top-dressed with a 50:50 mix by weight of ammonium sulfate (21-0-0) and urea with nitrogen inhibitor (45-0-0) at a rate of 224 kg ha^{-1} on April 24, 2018. Similar fertilizer applications were made from 2015 through 2017.

Figure 9: Strip-tillage treatment being applied using Unverferth Zone Builder Subsoiler Model 122.

Figure 10: Soil disturbance after strip-tillage with Unverferth Zone Builder Subsoiler Model 122.

3.3.2 Data Collection

Data were collected during August 2018 at physiological grain maturity, coinciding with the fourth grain harvest from the field. Biomass was harvested by hand from two 0.5 m^2 quadrats in each plot on August 31. One quadrat was placed in a representative location in each of the north and south halves of the plot selected to avoid edge effects. Within each quadrat, all plant tissue was clipped at the soil surface and separated into crop or weed in the field. Weed species present were recorded for each plot. Crop biomass was separated into stems and seedheads in the field and both were counted. All biomass samples were then dried at 65 C for a minimum of five days before weighing. Seedhead samples were further processed to assess hand-harvested yield and components of yield. Twenty seedheads were randomly selected from each sample to be hand threshed and the grain dehulled, with seedhead length, spikelet count, floret count, and seed count all recorded for these subsamples. The remaining seedheads from each sample were then threshed and dehulled with a hand deawner/debearder (Hoffman Manufacturing Inc., Corvallis, Oregon, USA). From these data, the percentage of tillers that were fertile (i.e. produced a seedhead), harvest index, and thousand kernel weight were also calculated. Non-seed biomass separated from seedheads during this process was added to stem biomass to obtain a value for total aboveground vegetative biomass for each sample. All grain yields reported were dehulled and corrected to 13% market moisture content.

3.3.3 Data Analysis

All data were analyzed using one-way ANOVA in R version 3.5.3 (R Core Team 2019). The lmer function from the lme4 package was used for linear mixed effects models for each response variable with tillage treatment as the fixed effect and block as a random effect. ANOVA assumptions were checked using the leveneTest function from the car package to confirm homogeneity of variance and the shapiro.test function from the stats package to confirm that residuals were normally distributed. Pseudo R-squared values and likelihood-ratio tests were calculated to assess model goodness-of-fit using the nagelkerke function from the rcompanion package. Post-hoc comparisons of marginal means using Fisher's protected LSD were conducted using the marginal, CLD, and pairs functions from the lsmeans package. All tests used α = 0.05 as the cutoff for significant effects.

3.4 Results

Fall strip-tillage increased grain yields compared with spring strip-tillage and control treatments (Table 15). Dehulled grain yield from the fall strip-tilled treatment increased 61% (P = 0.025) relative to the control treatment. Total tiller density m^{-2} was marginally reduced by 24% in the fall strip-tillage treatment when compared to the control treatment (P = 0.058). Spring strip-tillage reduced tiller density to a greater extent, with tiller counts 29% lower (P = 0.030) than the untilled control. Stand density was similar between fall and spring strip-tillage treatments (P = 0.679). Fertile tiller density (i.e. tillers bearing mature seedheads m^{-2}) was highest in fall-tilled plots, 43% higher than the control (P = 0.035) and 86% higher than the spring-tilled plots (P = 0.005). Thus, the overall effect of the fall strip-tillage treatment was to increase tiller fertility (i.e. the percentage of tillers that produced a mature seedhead) from 19% in the control treatment to 35% in the fall strip-tillage treatment (p-value = 0.003), leading to an increased grain yield after fall strip-tillage. Tiller fertility in the spring strip-tillage treatment was similar to the control treatment (*P* = 0.9067).

Total crop biomass was similar between fall strip-tillage and control treatments (*P* = 0.3579) at around 7000 kg ha^{-1}. Spring strip-tillage reduced crop biomass by 27% (*P* = 0.005) compared to the control treatment. There were no differences between treatments for yield components including counts of spikelets, florets, or seeds per seedhead, or thousand kernel weight (Table 15). Harvest index was higher in the fall strip-tillage treatment than the control treatment (*P* = 0.0129) due to the combination of higher grain yields and marginally lower total crop biomass production. Harvest index for spring-tilled plots was intermediate between, and similar to, the harvest index for both the fall-tilled and the untilled control plots. Weed biomass was low across the experiment and no differences were observed between treatments.

Table 15: Summary of ANOVA results for mean (SE) components of yield from fourth year Kernza intermediate wheatgrass harvested in the season following fall, spring, or no (control) management disturbance from strip-tillage. N = 5. Treatment means within each yield component sharing the same letter are not significantly different at α = 0.05.

Yield Components	**Units**	**$F_{2,8}$**	**Pr(>F)**	**Fall**	**Spring**	**Control**
Grain yield	kg ha^{-1}	5.172	0.036	219.4 (34.0) a	134.3 (26.9) b	136.4 (4.4) b
Crop biomass	kg ha^{-1}	7.726	0.007	6775 (475) a	5300 (375) b	7290 (220) a
Harvest index	kg kg^{-1}	5.086	0.038	0.032 (0.005) a	0.025 (0.004) ab	0.019 (0.001) b
Tiller density	m^{-2}	4.023	0.046	763.0 (47.5) ab	716.2 (56.8) a	1004.0 (110.8) b
Seedhead count	m^{-2}	7.741	0.013	261.2 (23.5) a	140.2 (29.8) b	182.2 (12.6) b
Tiller fertility	%	11.215	0.005	34.7 (4.0) a	19.2 (3.1) b	18.8 (1.7) b
Spikelet count	$seedhead^{-1}$	0.175	0.842	17.1 (0.6) a	16.9 (0.6) a	16.6 (0.5) a
Floret count	$seedhead^{-1}$	0.855	0.461	56.0 (5.3) a	56.5 (4.0) a	50.6 (2.0) a
Seed count	$seedhead^{-1}$	0.313	0.740	29.6 (3.6) a	31.0 (2.7) a	28.4 (1.9) a
Thousand kernel wt.	g	0.025	0.975	5.09 (0.16) a	5.05 (0.03) a	5.07 (0.16) a
Weed biomass	kg ha^{-1}	0.432	0.664	182.22 (113.6) a	115.80 (78.8) a	76.52 (33.5) a

3.5 Discussion

Strip-tillage in the fall substantially increased grain yield in the subsequent harvest, demonstrating that stand thinning can improve grain yields in older Kernza stands. Reducing overall stand density, and likely intraspecific competition, appears to have allowed the remaining Kernza plants to grow more vigorously and produce more seedheads per unit area given enough time between disturbance and harvest. Strip-tillage treatments did not affect spikelet and floret counts per seedhead at harvest, however, indicating that differences in seed production were not driven by differences in inflorescence size that have been reported in other perennial grasses (Abel et al., 2017). Even strip-tillage in the spring reduced competition between reproductive tillers as there was no difference in yield despite lower stand density compared to the control. Similar effects on seedhead density were reported in previous work using stand thinning to stimulate seed production of other perennial cool-season grasses. In a study using Kentucky bluegrass (*Poa pratensis* L.), Evans (1980) found edge effects affecting panicle density, with higher panicle density closer to areas where sections of row had been removed after seed harvest and lower density in areas further from disturbance, suggesting competition for light and space decreased floral induction. The disturbance caused by strip-tillage is likely to have altered some environmental conditions, including light quality, that influence floral induction, but other factors such as photoperiod and temperature are more seasonally dependent (Kalton et al., 1996). Stand-thinning via strip-tillage after harvest could also increase seed production in the following year by stimulating new growth that has higher capacity for photosynthesis and carbon assimilation during seed development, but may have lower tolerance of extreme cold and other abiotic stress (Jaikumar et al., 2016). Tillage practices may also influence soil nutrient availability by altering soil conditions and stimulating decomposition of soil organic matter (Gómez-Rey et al., 2012), but this effect was not examined in this experiment.

Differences between the fall and spring strip-tillage treatments indicate that the timing of disturbance used for stand thinning is important. In this experiment, spring-tillage reduced overall stand density by a similar amount as fall-tillage, but crop biomass production, tiller fertility, and grain yields were lower after spring-tillage indicating lower crop vigor after disturbance in the spring. Previous research on the impact of spring forage harvest timing on intermediate wheatgrass tiller persistence found that disturbance prior to stem elongation was associated with lower tiller mortality than disturbance later in the growing season (Hendrickson et al., 2005). It is possible that disturbance after plants break dormancy in the spring is not conducive to seed production, either due to added stress during a critical period of growth or incompatibility with plant phenology. The annual reproductive cycle of intermediate wheatgrass begins with tiller development during regrowth after harvest, followed by reproductive tiller induction during overwintering, and floral development the following spring (Cattani and Asselin, 2017; Heide, 1994; Majerus, 1988). Disturbance at later stages of this process would therefore have greater potential to reduce fertile tiller density as there would be less opportunity for reproductive tiller replacement even if resources were otherwise abundant. Some perennial grasses are able to produce new reproductive tillers in the spring after vernalization, but these tillers tend to be smaller and produce fewer seeds and disturbance after this secondary induction would only stimulate regrowth of vegetative tillers (Abel et al., 2017). Moreover, any tillers that are newly established in the spring may compete for resources with larger tillers produced the previous fall, potentially reducing seed yield via reduced inflorescence size or reduced seed set (Aamlid et al., 1998). It is also plausible, however, that disturbance during spring in our experiment, which did not negatively impact grain yields relative to the control, might have a positive effect on yield at the second harvest after treatment. An alternative mechanism

Fourth-year Kernza grain yields obtained in our study are comparable to yields reported in two recent field experiments in Minnesota. In a study examining the effects of row spacing and crop defoliation on grain yield, Hunter et al. (2020a) reported a mean grain yield of 276 kg ha^{-1} across all management treatments, slightly higher than the 219 kg ha^{-1} from our fall strip-tillage treatment. The Minnesota study utilized Cycle 4 Kernza seed, and thus genetic improvement may be partly responsible for higher average grain yields. Increased row spacing also had a positive effect on grain yields in their study, with an average fourth-year yield for their 15-cm row spacing treatment of 244 kg ha^{-1}, a yield similar to our fall strip-tillage value. In a study examining the effects of inter-row cultivation, herbicide application, burning, and mowing on Kernza yield, Bergquist (2020) reported fourth-year Kernza grain yields ranging between 50 and 300 kg ha^{-1}. Grain yield after fall inter-row cultivation averaged 231 kg ha^{-1}, which is similar to yields for our fall strip-tillage treatment but was not statistically different from their control treatment yield of 208 kg ha^{-1}.

Prior to this experiment, Kernza grain yields measured in a separate part of the same field but not within the area of this experiment exhibited steady decline from 930 kg ha^{-1} in 2015, the first year after planting, to 600 kg ha^{-1} in 2016, and 315 kg ha^{-1} in 2017, the third year after planting and the harvest just before strip-tillage was implemented (data not shown). These grain yields show a similar pattern of decline in seed production as other reports in the literature. Hunter et al. (2020a) report first year Kernza grain yields of 775 kg ha^{-1} declining to 300 kg ha^{-1} by the third year of their experiment, and Bergquist et al. (2020) report average grain yields of 340 kg ha^{-1} and 50 kg ha^{-1} in their second and third years, respectively. Total crop biomass measured in the same field as our experiment averaged 5000 kg ha^{-1} yr^{-1} for each of the first three growing seasons (data not shown), which is on the low end of the typical range of 5000 – 11000 kg ha^{-1} reported in the literature (Bergquist, 2020; Dick et al., 2018; Hunter et al., 2020b; Jungers et al., 2017; Tautges et al., 2018). Total crop biomass did increase to ~7000 kg ha^{-1} in the fall strip-tillage and control treatment plots in 2018, which is consistent with many reports of total biomass production increasing as Kernza stands age.

The intensity of disturbance may be an important factor in determining whether management aids or hinders Kernza grain yields. While our study did not vary the type of disturbance or disturbance intensity, other research has demonstrated that higher-intensity disturbance using banded herbicide applications or more intense tillage have not improved or maintained Kernza grain yield (Bergquist, 2020). Striking a balance with management interventions that optimize reproductive sink capacity by reducing competition between tillers without causing excessive damage that hinders crop vigor is an important stand management goal that warrants further research (Hunter et al., 2020a). Moreover, other types of targeted disturbance that differ in intensity and their effect on the crop should be assessed as options for managing Kernza and other perennial grains. For example, burning straw and stubble after harvest of intermediate wheatgrass was more effective than mechanical thinning at maintaining high seed yields in one early study (Canode, 1965). Clearly, there are many types of cultivation and chemical thinning strategies that require research attention.

3.5.1 Limitations and recommendations for further research

As this experiment was not replicated in time or space, we encourage further investigation of stand-thinning using strip-tillage before proposing broader recommendations for utilizing strip-tillage in Kernza production. Based on these results and evidence from other published studies, future research on using strip-tillage to maintain Kernza yields should focus on the specific timing and intensity of disturbance during the fall, including treatments implemented soon after grain harvest. Moreover, data should be collected over multiple growing seasons to better understand any longer-term effects of the disturbance. We also recommend research into the effects of strip-tillage after the first and second grain harvests from Kernza stands when grain yields are still relatively high. For example, would strip-tillage after the second grain harvest increase grain yield of the third harvest similar to the increase we observed from strip tillage between the third to fourth grain harvests in this study?

3.6 Conclusion

Kernza intermediate wheatgrass has the potential to improve the sustainability of cereal grain production by contributing additional ecosystem services including soil health improvement, water quality protection, and potential for soil carbon storage. Improving grain yield of Kernza through optimized crop management will facilitate adoption of the crop, allowing these environmental benefits to be gained across a wider range of agricultural systems. In this experiment, strip-tillage of a Kernza stand in late fall after the third grain harvest increased grain yield of the fourth harvest the following year. This effect was likely due to a reduction in intraspecific competition between reproductive tillers after tillage. Strip-tillage applied in early spring reduced stand density but did not impact yields. Further research into different types, timings, and intensities of disturbance should be a priority in developing management recommendations for Kernza and other perennial grain crops.

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EPILOGUE

In this dissertation I report on the multiple field experiments and sustainability analyses of the perennial grain crop Kernza® intermediate wheatgrass (IWG) that I conducted during my PhD research. Based on the results of this research, IWG has great potential to increase the environmental and economic sustainability of integrated crop-livestock systems in the Northeastern United States in the near future. The projects reported in this dissertation represent just a fraction of the research that I have done on IWG and a second perennial grain crop, ACE-1 perennial cereal rye, during the five years that I have spent at Cornell. These and other perennial grains still require significant improvement through breeding to close yield gaps with annual grains and improve agronomic traits such as free-threshability that currently hinder their production and processing efficiency. There are also still many questions to be answered regarding how to manage them in monoculture, in simple and complex polycultures, and in rotation with other perennial and annual crops. Despite current challenges, some of which are highlighted in the preceding chapters, there has been rapid advancement in perennial crop breeding, agronomic best management practices, processing and market infrastructure, and scientific evidence for the environmental benefits of these crops over the past five years. As one metric of the development of this field of research, a quick Google Scholar search for “perennial grain” yields 88 results for the year 2016 when I began my research on IWG and perennial cereal rye, which increased more than twofold to 186 publications in 2020. Being at the forefront of this research in several areas including systems-level sustainability analyses and integrated weed management has been the highlight of my PhD research program and I look forward to continuing to contribute to the science and practice of perennial grain crop production as I move forward in my academic career.

In Chapter 1, I studied the agronomic productivity of IWG in monoculture and intercropped with medium red clover. Winter wheat was also grown both with and without red clover to provide a comparison to an annual small grain that is commonly grown by organic farmers in New York. Components of yield were measured in an effort to provide additional information about the physiological processes governing grain yield of Kernza. Weed communities were documented to provide insight into how a perennial crop might influence weed community structure, and vice-versa. Information on problematic weeds will also be used to inform further research on weed management strategies for Kernza and other perennial grain crops.

The results presented in Chapter 1 contribute to our collective understanding of IWG cropping systems, but this project was truly a learning experience and there are many things that I would do differently if I were to repeat it. As mentioned above, this project originally included perennial cereal rye as a second perennial grain crop but those results were excluded from this dissertation for a number of reasons. First, while the perennial rye established well and produced a relatively high amount of grain and forage in its first year, its post-harvest regrowth was not as vigorous as IWG and it struggled to compete with both the red clover intercrop and other weeds. This led to very poor performance during the second growing season and we decided to not collect data from the perennial rye treatments during the third growing season. Perennial cereal rye data from the first two years will be published in the future, but I regret not following that treatment during the third year because it complicated the experimental design and made it more difficult to include those results in is dissertation. While that aspect of the project was in some respects a failure, we now know more about the agronomic challenges that need to be addressed to before ACE-1 perennial cereal rye can be a viable crop and data on the grain and forage biomass of the perennial cereal rye helped place the IWG results into a broader context of perennial grain cropping systems.

In Chapter 2, I utilize data on crop productivity and production inputs from management records to conduct several economic and environmental sustainability analyses of the perennial IWG and annual winter wheat systems that were studied in chapter 2. These analyses include measuring changes in soil health indicators over time, enterprise budget and sensitivity analyses to estimate Kernza grain prices that would be profitable for farmers under a variety of economic scenarios, energy consumption and greenhouse gas emission estimates calculated with the Farm Energy Analysis Tool, and an assessment of the relative importance of local, renewable resources versus external, purchased inputs in IWG production using the emergy synthesis method. Additional measures of sustainability that could have added to the holistic evaluation of IWG cropping systems include direct measurement of soil erosion, assessment of cropping system impacts on agrobiodiversity including insect pollinators, birds, and soil biota, and quantification of changes in soil carbon that would provide evidence of net soil carbon storage that has frequently been hypothesized to be a benefit of perennial cropping systems. Different methods of allocating energy consumption and GHG emissions to crop products could have also altered our conclusions. An economic allocation, where energy and GHG metrics are calculated per dollar value of crop products, would have provided further insight into the economic tradeoffs caused by the low grain production of IWG. This allocation is not reported because market prices for IWG grain are not available, and thus the analysis would have required significant assumptions. As markets for IWG grain and other perennial grains develop this type of analysis would be useful to farmers that as they make decisions that affect the economic sustainability of their businesses.

Including a corn-soybean-spelt rotation in addition to the IWG and wheat systems allowed me to respond to some criticisms of the IWG/wheat experiment that I would like to address briefly here. A continuous wheat cropping system would not be an ideal comparison if one were solely interested in determining how IWG compares as an alternative to what are currently widely adopted practices for organic grain production in New York. It is also important to remember, however, that context and perspective matter in our scientific experimentation, and while in many cases we strive to make our research practical and applicable to farmers, there are constraints that limit our ability to answer more than one or perhaps a few questions with a single experiment. As it was designed, the experiment comparing perennial and annual small grain crops was not meant to represent optimized cropping systems. In fact, this comparison represents the complete opposite, in that when this experiment began we knew so little about how IWG and perennial cereal rye would perform in New York that we attempted to simplify the experimental design as much as possible. In addition, it is important to keep in mind that the basic scientific questions that we were asking at that stage were not whether IWG or perennial cereal rye can immediately be as productive as a well-established organic cropping rotation, but rather, what state variables, interactions, and flows are similar or different between annual and perennial small grain production systems when they are intentionally managed such that "annual" versus "perennial" is the focal variable that informs our objectives.

When considered in this way, it is clear why we would not compare two novel perennial crops with a relatively complex rotation that would have introduced numerous confounding variables and made it much more difficult to contextualize our observations. In looking at the data for the corn-soybean-spelt rotation that we did eventually use for comparison it is immediately obvious that drawing conclusions about differences between the perennial systems as they aged and three different annual crop species with different life histories, all of which were fertilized at different rates, and had different levels of mechanical weed control applied to them could have become very difficult. Ultimately, the ongoing value of the research presented in this dissertation is that it allowed us to identify areas where our lack of knowledge about perennial grain production had large impacts on experimental outcomes, and from there, potential broader implications for future adoption and management of the crop. For example, how can the perennial crops be best managed after harvest during the critical period of regrowth that has implications for yield potential the following year and allows them store enough energy to successfully overwinter? That being said, cropping systems research projects that compare IWG to annual crop rotations, or incorporate IWG into those rotations, preferably with multiple entry points for the IWG crop, would greatly aid us in understanding how IWG can fit into a whole-farm management strategy.

As discussed above and in Chapters 1 and 2, there were two major limitations to our interpretation of the data from that experiment. Namely, we only collected data from a single planting year of IWG and we compared the IWG crop with a continuous crop of winter wheat, which is not a practice that New York farmers would use. Due to only having data from a single planting year of IWG we were not able to separate the impacts of adverse weather conditions from the effects of IWG stand age, despite there being some evidence that drought reduced IWG seed production in 2018. Future research should collect agronomic data from multiple IWG stands planted across a range of climatic conditions through multiple years to allow a full analysis of the effects of drought and other environmental factors on IWG physiology and productivity. This type of study would require collaborative effort among scientists studying IWG to generate the necessary data. Comparing IWG with three consecutive years of winter wheat was done to provide a straight-forward comparison of the perennial and annual cropping systems, but it was evident by the third year that weed competition was increasing in wheat plots and disease incidence and severity was likely increasing as well due to the overwintering of pathogens in soil and crop residues. Further experiments comparing IWG to wheat could plant wheat in different locations each year, but any differences in soil, precipitation, or other environmental factors could create other confounding effects. With large, comprehensive datasets more advanced statistical analyses such as structural equation modeling or path analysis would allow us to evaluate the relative importance of the factors on crop yield or other response variables. This would again be greatly aided by coordinated collaborative efforts to evaluate IWG relative to a variety of other crops and growing conditions.

In Chapter 3, I studied the impact of strip-tillage in the fall and spring on the grain yield of IWG at the following harvest. This study was developed in response to the many reports of IWG grain yield declining as stands age. In conversations with colleagues studying IWG agronomy intraspecific competition was proposed as a potential cause of this phenomenon. Our first attempt at a strip-tillage experiment, titled Grain Legume Intercropping in Kernza (GLIK) failed due to poor timing of tillage in the spring after stem elongation had begun. GLIK also suffered by being too ambitious in its treatments, as including a factorial of strip-tillage and grain legume treatments created a complex experimental design that was difficult to manage from an agronomic standpoint. The strip-tillage experiment that was ultimately successful was also disrupted by a farm equipment malfunction that resulted in far too much fertilizer being applied to one area of the field, preventing data collection from the second grain harvest after strip-tillage. This experience taught me quite a lot about experimental design and clearly identifying the goals of an experiment. I was also reminded that well-laid plans can always be thrown off course by unexpected and uncontrollable circumstances, and that adapting to these challenges will always be a necessary skill. The experience also gave me confidence to trust my own expert knowledge when I needed to advocate for resources to be dedicated to sampling an experiment that many had given up on. The results of this project have real, practical significance for IWG management and I have found that to be very rewarding.

Further research on managing IWG stands to maintain grain yield should expand the range of timing of strip-tillage along two temporal scales. First, the optimal timing of fall strip-tillage could be determined by comparing the effects of different tillage dates, ideally starting quite soon after grain harvest and continuing periodically through the end of plant growth at the end of the season. This research could also include more extensive sampling of IWG growth characteristics such as tiller density, plant height, and above- and belowground biomass production during the fall regrowth period to provide a better understanding of the physiological mechanisms affecting the IWG reproductive cycle. Second, examining the effects of strip-tillage after the first, second, and third IWG grain harvests may help maintain relatively high grain yields throughout the intended life of a stand, and could provide further insight into possible genetic and physiological mechanisms governing IWG seed production.

In the prologue I summarize the global challenges facing agriculture and describe how perennial grain crops might be able to contribute to efforts to make agriculture more economically and environmentally sustainable. This dissertation focuses on Kernza intermediate wheatgrass as it is the perennial grain crop that is closest to widespread adoption by farmers in the United States. An outline of the current scientific understanding of the potential opportunities for IWG to contribute to more sustainable agroecosystems is presented and the barriers to achieving those goals are identified.

While the research in this dissertation represents substantial development of perennial IWG cropping systems in the Northeastern United States, there are larger, systemic issues in the global agrifood system that are not addressed in this work and cannot be solved simply by growing new crops, no matter how productive they are or how much they can improve indicators of environmental benefits. Environmental externalities are so endemic to the entire food value chain that it is seen as a win when incremental improvements are made in in water, air, or soil quality, and transformational improvements (e.g., net zero carbon emissions) are perceived to be out of reach. Exploitation of labor, and particularly the vulnerability of undocumented migrant workers, is seen as a sound business strategy. The gap between the most and least privileged members of our society continues to grow to the point that it becomes difficult for either side to comprehend the experiences of the other, preventing or at least complicating the formation of any collective efforts to address these inequities. I do not pretend to fully understand, much less propose solutions to, these challenges but I do want to acknowledge that they exist and that progress will not be made if we continue to separate our work as agricultural scientists from these critical issues of justice.

APPENDIX A: SUPPLEMENTAL MATERIALS FOR CHAPTER 1

Table A1: Treatment means for three-way interactions between grain crop, intercrop, and year for crop productivity and weed community metrics. Interactions were not significant at α=0.05 but data are provided for reference purposes.

Grain Crop	**Intercrop**	**Year**	**Grain yield**	**Straw biomass**	**Harvest index**	**Red clover biomass**	**Forage yield**	**Weed biomass**	**Percent perennial weeds**	**Weed species richness**	**Weed species evenness**
			------ kg ha^{-1} ------		kg kg^{-1}	----------- kg ha^{-1} -----------			%	species m^{-2}	unitless
Kernza	Clover	2017	1124	5632	0.148	809	6441	730	26.2	11.00	0.619
		2018	256	4300	0.047	3004	7304	360	97.8	2.75	0.174
		2019	533	8412	0.053	425	8837	390	98.7	2.75	0.528
	No Clover	2017	1380	5634	0.174	0	5634	1339	64.2	12.75	0.612
		2018	189	3900	0.042	0	3900	1567	86.4	9.75	0.473
		2019	385	7425	0.043	0	7425	1553	85.4	9.25	0.523
Wheat	Clover	2017	3311	4850	0.368	456	5306	112	34.1	7.00	0.700
		2018	3310	3450	0.451	196	3646	409	56.6	6.75	0.486
		2019	2786	3670	0.390	580	4250	679	26.8	13.25	0.620
	No Clover	2017	3733	5700	0.362	0	5700	134	58.4	9.50	0.684
		2018	2238	2800	0.401	0	2800	357	32.0	11.00	0.542
		2019	2217	3471	0.357	0	3471	1053	21.1	15.50	0.590

Table A2: Treatment means for three-way interactions between grain crop, intercrop, and year for components of grain yield. Interactions were not significant at α=0.05 but data are provided for reference purposes.

Grain Crop	**Intercrop**	**Year**	**Tiller count**	**Seedhead count**	**Fertile tillers**	**Seedhead weight**	**Seedhead length**	**Floret count**	**Seed count**	**Seed size**
			m^{-2}	m^{-1}	%	g $seedhead^{-1}$	cm $seedhead^{-1}$	$seedhead^{-1}$	$seedhead^{-1}$	TKW [1]
Kernza	Clover	2017	396	291	75.6	0.519	24.1	61.9	48.2	7.2
		2018	246	194	80.0	0.253	18.8	51.6	27.3	6.7
		2019	585	352	62.0	0.291	19.7	56.1	30.0	5.5
	No Clover	2017	424	345	80.5	0.481	23.2	57.8	47.7	7.8
		2018	348	195	56.4	0.185	16.4	40.6	22.9	6.4
		2019	528	278	50.2	0.278	17.2	44.5	25.0	6.7
Wheat	Clover	2017	512	493	96.4	0.807	7.4	38.7	26.0	35.0
		2018	449	435	96.6	0.885	6.2	44.7	26.2	32.3
		2019	387	351	89.7	0.511	7.8	38.3	24.4	28.0
	No Clover	2017	517	484	93.7	0.907	7.8	45.1	31.1	35.6
		2018	420	365	87.7	0.722	6.1	44.1	28.1	30.8
		2019	364	319	88.2	0.479	7.5	34.6	21.7	28.1

[1] Thousand kernel weight in grams.

APPENDIX B: SUPPLEMENTAL MATERIALS FOR CHAPTER 2

Table B1: Enterprise budget for a three-year organic IWG-red clover polyculture in central New York.

	Category	Output/Input	Units	2017	2018	2019	Total Value[1]	
Revenue	Grain	Yield	kg/ha	1124	256	533		
		Market price	$/kg	1.32	1.25	1.19		
		Gross revenue	$/ha	1483.81	321.05	635.02	2439.89	
	Straw/Hay	Yield	kg/ha	5159	7304	8837		
		Market price	$/kg	0.15	0.14	0.13		
		Gross revenue	$/ha	764.39	1028.10	1181.68	2974.17	
	Annual revenue		$/ha	2248.20	1349.15	1816.70		
						Total revenue:	5414.05	$/ha
Production Costs	Field operations	Moldboard plow	$/ha	54.36	-	-	54.36	
		Disk harrow	$/ha	42.01	-	-	42.01	
		Cultipacker	$/ha	42.50	-	-	42.50	
		Dry fertilizer application	$/ha	17.30	16.43	15.61	49.34	
		Small grain drill	$/ha	43.49	-	-	43.49	
		Grain harvest (combine & local haul)	$/ha	77.84	73.95	70.25	222.03	
		Complete hay harvest (mow, bale, haul)	$/kg	0.02	0.02	0.02		
		Hay Yield	kg/ha	5159	7304	8837		
		Gross cost	$/ha	100.67	135.41	155.63	391.71	
	Kernza seed	Seeding rate	kg/ha	16.8	-	-		
		Seed price	$/kg	13.23	-	-		
		Gross cost	$/ha	222.26	-	-	222.26	
	Red clover seed	Seeding cate	kg/ha	22.4	22.4	-		
		Seed price	$/kg	7.94	7.94	-		
		Gross cost	$/ha	177.81	168.92	-	346.73	
	Poultry litter	Fertilizer rate	kg/ha	1800	1800	1800		
		Fertilizer price	$/kg	0.40	0.38	0.36		
		Gross cost	$/ha	714.42	678.70	644.76	2037.88	
	Land	Rental cost	$/ha	150.73	147.89	147.19	445.81	
	Organic certification		$/ha	7.41	7.04	6.69	21.15	
	Annual costs		$/ha	1650.82	1228.34	1040.14		
						Production costs subtotal:	3919.29	$/ha
	Interest	5% of production costs	$				195.56	
						Total production costs:	4115.26	$/ha
						Net present value:	1298.80	$/ha

		Mean annual income:	432.93 $/ha

Table B2: Enterprise budget for three-year continuous organic IWG monoculture in central New York.

	Category	Output/Input	Units	2017	2018	2019	Total Value[1]	
Revenue	Grain	Yield	kg/ha	1380	189	385		
		Price	$/kg	1.37	1.30	1.23		
		Gross Income	$/ha	1886.78	245.49	475.06	2607.33	
	Straw/Hay	Yield	kg/ha	4900	4498	7465		
		Price	$/kg	0.15	0.14	0.13		
		Gross Income	$/ha	726.01	633.13	998.22	2357.36	
	Annual revenue		$/ha	2612.79	878.62	1473.28		
						Total revenue:	4964.69	$/ha
Production Costs	Field operations	Moldboard plow	$/ha	54.36	-	-	54.36	
		Disk harrow	$/ha	42.01	-	-	42.01	
		Cultipacker	$/ha	42.50	-	-	42.50	
		Dry fertilizer application	$/ha	17.30	16.43	15.61	49.34	
		Small grain drill	$/ha	43.49	-	-	43.49	
		Grain harvest (combine & local haul)	$/ha	77.84	73.95	70.25	222.03	
		Complete hay harvest (mow, bale, haul)	$/kg	0.02	0.02	0.02		
		Hay Yield	kg/ha	4900	4498	7465		
		Gross cost	$/ha	95.62	83.39	131.47	310.48	
	Kernza seed	Seeding rate	kg/ha	16.8	-	-		
		Seed price	$/kg	13.23	-	-		
		Gross cost	$/ha	222.26	-	-	222.26	
	Poultry litter	Fertilizer rate	kg/ha	1800	1800	1800		
		Fertilizer price	$/kg	0.40	0.38	0.36		
		Gross cost	$/ha	714.42	678.70	644.76	2037.88	
	Land	Rental cost	$/ha	150.73	147.89	147.19	445.81	
	Organic certification		$/ha	7.41	7.04	6.69	21.15	
	Annual costs		$/ha	1467.95	1007.40	1015.97		
						Production costs subtotal:	3491.32	$/ha
	Interest	5% of production costs	$				174.57	
						Total production costs:	3665.89	$/ha
						Net present value:	1298.80	$/ha
						Mean annual income:	432.93	$/ha

Table B3: Enterprise budget for three-year continuous organic hard red winter wheat - red clover polyculture in central New York.

	Category	Output/Input	Units	2017	2018	2019	Total Value[1]	
Revenue	Grain	Yield	kg/ha	3311	3310	2786		
		Price	$/kg	0.43	0.41	0.39		
		Gross Income	$/ha	1427.59	1355.80	1084.11	3867.50	
	Straw/Hay	Yield	kg/ha	5306	3646	4250		
		Price	$/kg	0.15	0.14	0.13		
		Gross Income	$/ha	770.25	502.81	556.80	1829.87	
	Annual revenue		$/ha	2197.84	1858.61	1640.91		
						Total revenue:	5697.36	$/ha
Production Costs	Field operations	Moldboard plow	$/ha	54.36	51.64	49.06	155.07	
		Disk harrow	$/ha	42.01	39.91	37.91	119.83	
		Cultipacker	$/ha	42.50	40.38	38.36	121.24	
		Dry fertilizer application	$/ha	17.30	16.43	15.61	49.34	
		Small grain drill	$/ha	43.49	41.32	39.25	124.06	
		Grain harvest (combine & local haul)	$/ha	77.84	73.95	70.25	222.03	
		Complete hay harvest (mow, bale, haul)	$/kg	0.02	0.02	0.02		
		Hay Yield	kg/ha	5306	3646	4250		
		Gross cost	$/ha	103.54	67.59	74.85	245.98	
	Wheat seed	Seeding rate	kg/ha	107.6	107.6	107.6		
		Seed price	$/kg	1.23	1.17	1.11		
		Gross cost	$/ha	132.86	126.22	119.91	379.00	
	Clover seed	Seeding cate	kg/ha	22.4	22.4	22.4		
		Seed price	$/kg	7.94	7.54	7.16		
		Gross cost	$/ha	177.81	160.47	160.47	498.76	
	Poultry litter	Fertilizer rate	kg/ha	1800	1800	1800		
		Fertilizer price	$/kg	0.40	0.38	0.36		
		Gross cost	$/ha	714.42	678.70	644.76	2037.88	
	Land	Rental cost	$/ha	150.73	147.89	147.19	445.81	
	Organic certification		$/ha	7.41	7.04	6.69	21.15	
	Annual costs		$/ha	1564.28	1451.55	1404.32		
						Production costs subtotal:	4420.15	$/ha
	Interest	5% of production costs	$				221.01	
						Total production costs:	4641.16	$/ha
						Net present value:	1056.21	$/ha
						Mean annual income:	352.07	$/ha

Table B4: Enterprise budget for three-year continuous organic hard red winter wheat monoculture in central New York.

	Category	Output/Input	Units	2017	2018	2019	Total Value[1]	
Revenue	Grain	Yield	kg/ha	3733	2238	2217		
		Price	$/kg	0.43	0.41	0.39		
		Gross Income	$/ha	1609.54	916.70	862.69	3388.94	
	Straw/Hay	Yield	kg/ha	5700	2802	3553		
		Price	$/kg	0.15	0.14	0.13		
		Gross Income	$/ha	827.45	386.42	465.49	1679.35	
	Annual revenue		$/ha	2436.99	1303.12	1328.18		
						Total revenue:	5068.29	$/ha
Production Costs	Field Operations	Moldboard plow	$/ha	54.36	51.64	49.06	155.07	
		Disk harrow	$/ha	42.01	39.91	37.91	119.83	
		Cultipacker	$/ha	42.50	40.38	38.36	121.24	
		Dry fertilizer application	$/ha	17.30	16.43	15.61	49.34	
		Small grain drill	$/ha	43.49	41.32	39.25	124.06	
		Grain harvest (combine & local haul)	$/ha	77.84	73.95	70.25	222.03	
		Complete hay harvest (mow, bale, haul)	$/kg	0.02	0.02	0.02		
		Hay Yield	kg/ha	5700	2802	3553		
		Gross cost	$/ha	111.23	51.94	62.57	225.75	
	Wheat seed	Seeding rate	kg/ha	107.6	107.6	107.6		
		Seed price	$/kg	1.23	1.17	1.11		
		Gross cost	$/ha	132.86	126.22	119.91	379.00	
	Poultry litter	Fertilizer rate	kg/ha	1800	1800	1800		
		Fertilizer price	$/kg	0.40	0.38	0.36		
		Gross cost	$/ha	714.42	678.70	644.76	2037.88	
	Land	Rental cost	$/ha	150.73	147.89	147.19	445.81	
	Organic Certification		$/ha	7.41	7.04	6.69	21.15	
	Annual costs		$/ha	1394.16	1275.42	1231.57		
						Production costs subtotal:	3901.16	$/ha
	Interest	5% of production costs	$				195.06	
						Total production costs:	4096.21	$/ha
						Net present value:	972.08	$/ha
						Mean annual income:	324.03	$/ha

Table B5: Enterprise budget for three-year organic corn-soybean-spelt rotation in central New York.

	Category	Output/Input	Units	2017	2018	2019	Total Value[1]	
				Corn	Soybean	Spelt		
Revenue	Grain	Yield	kg/ha	8278	2614	2585		
		Market price	$/kg	0.28	0.70	0.24		
		Gross revenue	$/ha	2297.07	1834.69	614.12	4745.88	
	Straw/Hay	Yield	kg/ha	0	0	0		
		Market price	$/kg	N/a	N/a	N/a		
		Gross revenue	$/ha	0.00	0.00	0.00	0.00	
	Annual revenue		$/ha	2297.07	1834.69	614.12		
						Total revenue:	4745.88	$/ha
Production Costs	Field operations	Moldboard plow	$/ha	54.36	51.64	49.06	155.07	
		Disk harrow	$/ha	42.01	39.91	37.91	119.83	
		Cultipacker	$/ha	42.50	40.38	38.36	121.24	
		Dry fertilizer application	$/ha	17.30	16.43	15.61	49.34	
		Planting	$/ha	52.39	47.42	39.25	139.06	
		Interrow cultivation	$/ha	139.61	83.77	-	223.38	
		Mowing	$/ha	-	26.76	25.42	52.18	
		Grain harvest (combine & local haul)	$/ha	77.84	73.95	70.25	222.03	
	Grain seed	Seeding rate	kg/ha	20.3	76.1	135		
		Seed price	$/kg	7.06	2.21	1.11		
		Gross cost	$/ha	143.24	167.80	150.44	461.48	
	Clover seed	Seeding rate	kg/ha	-	-	16.8		
		Seed price	$/kg	-	-	7.16		
		Gross cost	$/ha	-	-	120.36	120.36	
	Poultry litter	Fertilizer rate	kg/ha	2000	0	1000		
		Fertilizer price	$/kg	0.40	0.38	0.36		
		Gross cost	$/ha	793.80	0.00	358.20	1152.00	
	Land	Rental cost	$/ha	150.73	147.89	147.19	445.81	
	Organic certification		$/ha	7.41	7.04	6.69	21.15	
	Annual costs		$/ha	1521.19	702.99	938.39		
						Production cost subtotal:	3282.93	$/ha
	Interest	5% of production costs	$				164.15	
						Total production costs:	3447.08	$/ha
						Net present value:	1298.80	$/ha
						Mean annual income:	432.93	$/ha

Table B6: Estimates of energy consumption and greenhouse gas emissions calculated using the Farm Energy Analysis Tool (Camargo et al., 2013) for a three-year organic IWG-red clover polyculture in central New York.

Farm inputs and outputs **Crop year**	**Kernza - Yr1**	**Kernza - Yr2**	**Kernza - Yr 3**	**Clover - Yr1**	**Clover - Yr2**	**Clover - Yr3**	**Total ha^{-1} yr^{-1}**
Field area (ha yr^{-1})	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Yield (Mg ha^{-1})	1.12	0.26	0.53	-	-	-	0.64
Residue removal after harvest (%)	0.90	0.90	0.90	0.90	0.90	0.90	1.80
Crop moisture at harvest (%)	0.214	0.131	0.164	-	-	-	0.170
Crop moisture at storage (%)	0.135	0.135	0.135	-	-	-	0.135
Poultry litter (kg DM ha^{-1})	1800.0	1800.0	1800.0	0.0	0.0	0.0	1800.0
Poultry litter N (kg ha^{-1})	90.0	90.0	90.0	0.0	0.0	0.0	90.0
Poultry litter P (kg ha^{-1})	72.0	72.0	72.0	0.0	0.0	0.0	72.0
Poultry litter K (kg ha^{-1})	54.0	54.0	54.0	0.0	0.0	0.0	54.0
Seed rate (kg ha^{-1})	16.8	0.0	0.0	22.4	22.4	0.0	20.5
Diesel fuel (L ha^{-1})	82.7	44.7	43.3	0.0	0.0	0.0	56.9
Drying (MJ yr^{-1})	322.9	0.0	55.1	-	-	-	126.0
Labor (hr ha^{-1})	2.2	1.1	1.0	0.0	0.0	0.0	1.4
Crop production (Mg WM yr^{-1})	1.12	0.26	0.53	-	-	-	0.64
Crop production (Mg DM yr^{-1})	0.97	0.22	0.46	-	-	-	0.55
Residue harvested (Mg DM yr^{-1})	4.4	4.3	8.4	0.8	3.0	0.4	7.1
Total crop biomass	5.3	4.5	8.9	0.8	3.0	0.4	7.7
Energy analysis							**MJ ha^{-1} yr^{-1}**
Poultry litter transport	237.5	237.5	237.5	0.0	0.0	0.0	237.5
Poultry litter production	2697.4	2697.4	2697.4	0.0	0.0	0.0	2697.4
Seed	1478.4	0.0	0.0	929.4	929.4	0.0	1112.4
Transportation of inputs	10.8	0.0	0.0	14.3	14.3	0.0	13.1
Equipment	160.7	84.6	82.9	0.0	0.0	0.0	109.4
Drying	322.9	0.0	55.1	0.0	0.0	0.0	126.0
Labor	64.8	32.3	30.7	0.0	0.0	0.0	42.6
Diesel fuel	3709.2	2004.9	1942.0	0.0	0.0	0.0	2552.0

Total energy (MJ ha^{-1} yr^{-1})	**8681.7**	**5056.6**	**5045.7**	**943.7**	**943.7**	**0.0**	**6890.5**
Greenhouse gas emissions analysis						**kg CO_2e ha^{-1} yr^{-1}**	
Poultry litter transport	20.3	20.3	20.3	0.0	0.0	0.0	20.3
Poultry litter production	111.3	111.3	111.3	0.0	0.0	0.0	111.3
Seed	29.0	0.0	0.0	46.5	46.5	0.0	40.7
Transportation of inputs	0.8	0.0	0.0	1.1	1.1	0.0	1.0
Equipment	10.4	5.5	5.4	0.0	0.0	0.0	7.1
Drying	25.8	0.0	4.4	0.0	0.0	0.0	10.1
Diesel fuel	266.6	144.1	139.6	0.0	0.0	0.0	183.4
N2O - manure application	600.6	600.6	600.6	0.0	0.0	0.0	600.6
N2O - aboveground crop residues, direct	2.0	0.5	1.0	0.0	0.0	0.0	1.2
N2O - belowground crop residues, direct	30.4	6.9	14.4	0.0	0.0	0.0	17.2
N2O - aboveground crop residues, indirect	0.5	0.1	0.2	0.0	0.0	0.0	0.3
N2O - belowground crop residues, indirect	6.8	1.6	3.2	0.0	0.0	0.0	3.9
N2O - total from crop residue	39.7	9.1	18.9	0.0	0.0	0.0	22.6
Total GHG (kg CO_2e ha^{-1} yr^{-1})	**1104.6**	**890.8**	**900.4**	**47.6**	**47.6**	**0.0**	**997.0**

Table B7: Estimates of energy consumption and greenhouse gas emissions calculated using the Farm Energy Analysis Tool (Camargo et al., 2013) for a three-year continuous organic IWG monoculture in central New York.

Farm inputs and outputs Crop year	Kernza - Yr1	Kernza - Yr2	Kernza - Yr 3	-	-	-	Total ha^{-1} yr^{-1}
Field area (ha yr^{-1})	1.0	1.0	1.0	0.0	0.0	0.0	1.0
Yield (Mg ha^{-1})	1.38	0.19	0.38	-	-	-	0.65
Residue removal after harvest (%)	0.90	0.90	0.90	0.90	0.90	0.90	1.80
Crop moisture at harvest (%)	0.197	0.135	0.188	-	-	-	0.173
Crop moisture at storage (%)	0.135	0.135	0.135	-	-	-	0.135
Poultry litter (kg DM ha^{-1})	1800.0	1800.0	1800.0	0.0	0.0	0.0	1800.0
Poultry litter N (kg ha^{-1})	90.0	90.0	90.0	0.0	0.0	0.0	90.0
Poultry litter P (kg ha^{-1})	72.0	72.0	72.0	0.0	0.0	0.0	72.0
Poultry litter K (kg ha^{-1})	54.0	54.0	54.0	0.0	0.0	0.0	54.0
Seed rate (kg ha^{-1})	16.8	0.0	0.0	0.0	0.0	0.0	5.6
Diesel fuel (L ha^{-1})	81.3	43.3	43.3	0.0	0.0	0.0	56.0
Drying (MJ yr^{-1})	311.4	0.0	74.3	-	-	-	128.6
Labor (hr ha^{-1})	2.1	1.0	1.0	0.0	0.0	0.0	1.4
Crop production (Mg WM yr^{-1})	1.38	0.19	0.38	-	-	-	0.65
Crop production (Mg DM yr^{-1})	1.19	0.16	0.33	-	-	-	0.56
Residue harvested (Mg DM yr^{-1})	4.9	3.9	7.4	0.0	0.0	0.0	5.4
Total crop biomass	6.1	4.1	7.8	0.0	0.0	0.0	6.0
Energy analysis							**MJ ha^{-1} yr^{-1}**
Poultry litter transport	237.5	237.5	237.5	0.0	0.0	0.0	237.5
Poultry litter production	2697.4	2697.4	2697.4	0.0	0.0	0.0	2697.4
Seed	1478.4	0.0	0.0	0.0	0.0	0.0	492.8
Transportation of inputs	10.8	0.0	0.0	0.0	0.0	0.0	3.6
Equipment	159.1	82.9	82.9				108.3
Drying	311.4	0.0	74.3	0.0	0.0	0.0	128.6
Labor	63.3	30.7	30.7	0.0	0.0	0.0	41.5
Diesel fuel	3646.3	1942.0	1942.0	0.0	0.0	0.0	2510.1

Total energy (MJ ha^{-1} yr^{-1})	**8604.1**	**4990.6**	**5064.9**	**0.0**	**0.0**	**0.0**	**6219.9**
Greenhouse gas emissions analysis							**kg CO_2e ha^{-1} yr^{-1}**
Poultry litter transport	20.3	20.3	20.3	0.0	0.0	0.0	20.3
Poultry litter production	111.3	111.3	111.3	0.0	0.0	0.0	111.3
Seed	29.0	0.0	0.0	0.0	0.0	0.0	9.7
Transportation of inputs	0.8	0.0	0.0	0.0	0.0	0.0	0.3
Equipment	10.3	5.4	5.4	0.0	0.0	0.0	7.0
Drying	24.9	0.0	5.9	0.0	0.0	0.0	10.3
Diesel fuel	262.1	139.6	139.6	0.0	0.0	0.0	180.4
N2O - manure application	600.6	600.6	600.6	0.0	0.0	0.0	600.6
N2O - aboveground crop residues, direct	2.5	0.3	0.7	0.0	0.0	0.0	1.2
N2O - belowground crop residues, direct	37.3	5.1	10.4	0.0	0.0	0.0	17.6
N2O - aboveground crop residues, indirect	0.6	0.1	0.2	0.0	0.0	0.0	0.3
N2O - belowground crop residues, indirect	8.4	1.2	2.3	0.0	0.0	0.0	4.0
N2O - total from crop residue	48.8	6.7	13.6	0.0	0.0	0.0	23.0
Total GHG (kg CO_2e ha^{-1} yr^{-1})	**1108.1**	**883.8**	**896.7**	**0.0**	**0.0**	**0.0**	**962.9**

Table B8: Estimates of energy consumption and greenhouse gas emissions calculated using the Farm Energy Analysis Tool (Camargo et al., 2013) for a three-year continuous organic hard red winter wheat-red clover polyculture in central New York.

Farm inputs and outputs							
Crop year	**Wheat - Yr1**	**Wheat - Yr2**	**Wheat - Yr 3**	**Clover - Yr1**	**Clover - Yr2**	**Clover - Yr3**	**Total ha^{-1} yr^{-1}**
Field area (ha yr^{-1})	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Yield (Mg ha^{-1})	3.3	3.3	2.8	-	-	-	3.1
Residue removal after harvest (%)	0.90	0.90	0.90	0.90	0.90	0.90	1.80
Crop moisture at harvest (%)	0.037	0.081	0.161	-	-	-	0.093
Crop moisture at storage (%)	0.135	0.135	0.135	-	-	-	0.135
Poultry litter (kg DM ha^{-1})	1800.0	1800.0	1800.0	0.0	0.0	0.0	1800.0
Poultry litter N (kg ha^{-1})	90.0	90.0	90.0	0.0	0.0	0.0	90.0
Poultry litter P (kg ha^{-1})	72.0	72.0	72.0	0.0	0.0	0.0	72.0
Poultry litter K (kg ha^{-1})	54.0	54.0	54.0	0.0	0.0	0.0	54.0
Seed rate (kg ha^{-1})	107.6	107.6	107.6	22.4	22.4	22.4	130.0
Diesel fuel (L ha^{-1})	63.7	63.7	63.7	0.0	0.0	0.0	63.7
Drying (MJ yr^{-1})	0.0	0.0	261.9	-	-	-	87.3
Labor (hr ha^{-1})	2.1	2.1	2.1	0.0	0.0	0.0	2.1
Crop production (Mg WM yr^{-1})	3.3	3.3	2.8	-	-	-	3.1
Crop production (Mg DM yr^{-1})	2.9	2.9	2.4	-	-	-	2.7
Residue harvested (Mg DM yr^{-1})	4.9	3.5	3.7	0.5	0.2	0.6	4.4
Total crop biomass	7.7	6.3	6.1	0.5	0.2	0.6	7.1
Energy analysis							**MJ ha^{-1} yr^{-1}**
Poultry litter transport	237.5	237.5	237.5	0.0	0.0	0.0	237.5
Poultry litter production	2697.4	2697.4	2697.4	0.0	0.0	0.0	2697.4
Seed	930.2	930.2	930.2	929.4	929.4	929.4	1859.6
Transportation of inputs	68.9	68.9	68.9	14.3	14.3	14.3	83.2
Equipment	156.8	156.8	150.5	-	-	-	154.7
Drying	0.0	0.0	261.9	0.0	0.0	0.0	87.3
Labor	63.6	63.6	63.6	0.0	0.0	0.0	63.6
Diesel fuel	2857.3	2857.3	2857.3	0.0	0.0	0.0	2857.3

Total energy (MJ ha^{-1} yr^{-1})	**7011.7**	**7011.7**	**7267.3**	**943.7**	**943.7**	**943.7**	**8040.6**
Greenhouse gas emissions analysis							**kg CO_2e ha^{-1} yr^{-1}**
Poultry litter transport	20.3	20.3	20.3	0.0	0.0	0.0	20.3
Poultry litter production	111.3	111.3	111.3	0.0	0.0	0.0	111.3
Seed	42.8	42.8	42.8	46.5	46.5	46.5	89.3
Transportation of inputs	5.4	5.4	5.4	1.1	1.1	1.1	6.5
Equipment	10.2	10.2	9.8	0.0	0.0	0.0	10.1
Drying	0.0	0.0	21.0	0.0	0.0	0.0	7.0
Diesel fuel	205.4	205.4	205.4	0.0	0.0	0.0	205.4
N2O - manure application	600.6	600.6	600.6	0.0	0.0	0.0	600.6
N2O - aboveground crop residues, direct	13.6	13.6	11.7	0.0	0.0	0.0	13.0
N2O - belowground crop residues, direct	33.9	33.9	28.6	0.0	0.0	0.0	32.1
N2O - aboveground crop residues, indirect	3.1	3.1	2.6	0.0	0.0	0.0	2.9
N2O - belowground crop residues, indirect	7.6	7.6	6.3	0.0	0.0	0.0	7.2
N2O - total from crop residue	58.2	58.1	49.2	0.0	0.0	0.0	55.2
Total GHG (kg CO_2e ha^{-1} yr^{-1})	**1054.1**	**1054.1**	**1065.7**	**47.6**	**47.6**	**47.6**	**1105.6**

Table B9: Estimates of energy consumption and greenhouse gas emissions calculated using the Farm Energy Analysis Tool (Camargo et al., 2013) for a three-year continuous organic hard red winter wheat monoculture in central New York.

Farm inputs and outputs **Crop year**	**Wheat - Yr1**	**Wheat - Yr2**	**Wheat - Yr 3**	**-**	**-**	**-**	**Total ha^{-1} yr^{-1}**
Field area (ha yr^{-1})	1.0	1.0	1.0	0.0	0.0	0.0	1.0
Yield (Mg ha^{-1})	3.7	2.2	2.2				2.7
Residue removal after harvest (%)	0.90	0.90	0.90	0.90	0.90	0.90	1.80
Crop moisture at harvest (%)	0.033	0.082	0.134	0.000	0.000	0.000	0.083
Crop moisture at storage (%)	0.135	0.135	0.135	0.000	0.000	0.000	0.135
Poultry litter (kg DM ha^{-1})	1800.0	1800.0	1800.0	0.0	0.0	0.0	1800.0
Poultry litter N (kg ha^{-1})	90.0	90.0	90.0	0.0	0.0	0.0	90.0
Poultry litter P (kg ha^{-1})	72.0	72.0	72.0	0.0	0.0	0.0	72.0
Poultry litter K (kg ha^{-1})	54.0	54.0	54.0	0.0	0.0	0.0	54.0
Seed rate (kg ha^{-1})	107.6	107.6	107.6	0.0	0.0	0.0	107.6
Diesel fuel (L ha^{-1})	62.3	62.3	62.3	0.0	0.0	0.0	62.3
Drying (MJ yr^{-1})	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labor (hr ha^{-1})	2.1	2.1	2.1	0.0	0.0	0.0	2.1
Crop production (Mg WM yr^{-1})	3.7	2.2	2.2	0.0	0.0	0.0	2.7
Crop production (Mg DM yr^{-1})	3.2	1.9	1.9	0.0	0.0	0.0	2.4
Residue harvested (Mg DM yr^{-1})	5.7	2.8	3.5	0.0	0.0	0.0	4.0
Total crop biomass	8.9	4.7	5.4	0.0	0.0	0.0	6.3
Energy analysis							**MJ ha^{-1} yr^{-1}**
Poultry litter transport	237.5	237.5	237.5	0.0	0.0	0.0	237.5
Poultry litter production	2697.4	2697.4	2697.4	0.0	0.0	0.0	2697.4
Seed	930.2	930.2	930.2	0.0	0.0	0.0	930.2
Transportation of inputs	68.9	68.9	68.9	0.0	0.0	0.0	68.9
Equipment	160.7	155.2	155.2				157.0
Drying	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labor	62.0	62.0	62.0	0.0	0.0	0.0	62.0
Diesel fuel	2794.4	2794.4	2794.4	0.0	0.0	0.0	2794.4

Total energy (MJ ha^{-1} yr^{-1})	**6951.1**	**6945.6**	**6945.6**	**0.0**	**0.0**	**0.0**	**6947.5**
Greenhouse gas emissions analysis							**kg CO_2e ha^{-1} yr^{-1}**
Poultry litter transport	20.3	20.3	20.3	0.0	0.0	0.0	20.3
Poultry litter production	111.3	111.3	111.3	0.0	0.0	0.0	111.3
Seed	42.8	42.8	42.8	0.0	0.0	0.0	42.8
Transportation of inputs	5.4	5.4	5.4	0.0	0.0	0.0	5.4
Equipment	10.4	10.1	10.1	0.0	0.0	0.0	10.2
Drying	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Diesel fuel	200.8	200.8	200.8	0.0	0.0	0.0	200.8
N2O - manure application	600.6	600.6	600.6	0.0	0.0	0.0	600.6
N2O - aboveground crop residues, direct	15.2	9.6	4.0	0.0	0.0	0.0	9.6
N2O - belowground crop residues, direct	38.1	22.9	22.9	0.0	0.0	0.0	28.0
N2O - aboveground crop residues, indirect	3.4	2.2	2.2	0.0	0.0	0.0	2.6
N2O - belowground crop residues, indirect	8.6	5.2	5.1	0.0	0.0	0.0	6.3
N2O - total from crop residue	65.3	39.9	34.2	0.0	0.0	0.0	46.4
Total GHG (kg CO_2e ha^{-1} yr^{-1})	**1057.0**	**1031.2**	**1025.5**	**0.0**	**0.0**	**0.0**	**1037.9**

Table B10: Estimates of energy consumption and greenhouse gas emissions calculated using the Farm Energy Analysis Tool (Camargo et al., 2013) for a three-year organic corn-soybean-spelt rotation in central New York.

Farm inputs and outputs							
Crop year	**Corn**	**Soybean**	**Spelt**	**-**	**-**	**Clover (w/spelt)**	**Total ha^{-1} yr^{-1}**
Field area (ha yr^{-1})	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Yield (Mg ha^{-1})	10.8	2.6	2.5			4.9	5.3
Residue removal after harvest (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Crop moisture at harvest (%)	0.000	0.000	0.000	-	-	-	0.000
Crop moisture at storage (%)	0.150	0.130	0.130	-	-	-	0.137
Poultry litter (kg DM ha^{-1})	2000.0	0.0	1000.0	0.0	0.0	0.0	1000.0
Poultry litter N (kg ha^{-1})	100.0	0.0	50.0	0.0	0.0	0.0	50.0
Poultry litter P (kg ha^{-1})	100.0	0.0	50.0	0.0	0.0	0.0	50.0
Poultry litter K (kg ha^{-1})	60.0	0.0	30.0	0.0	0.0	0.0	30.0
Seed rate (kg ha^{-1})	20.3	76.1	135.0	0.0	0.0	16.8	82.7
Diesel fuel (L ha^{-1})	79.0	71.6	62.1	0.0	0.0	0.0	70.9
Drying (MJ yr^{-1})	0.0	0.0	0.0	-	-	-	0.0
Labor (hr ha^{-1})	2.8	2.6	1.8	0.0	0.0	0.0	2.4
Crop production (Mg WM yr^{-1})	10.8	2.6	2.5	-	-	-	5.3
Crop production (Mg DM yr^{-1})	9.1	2.3	2.2	-	-	-	4.5
Residue harvested (Mg DM yr^{-1})	0.0	0.0	0.0	-	-	-	0.0
Total crop biomass	9.1	2.3	2.2	0.0	0.0	0.0	4.5
Energy analysis							**MJ ha^{-1} yr^{-1}**
Poultry litter transport	263.9	0.0	132.0	0.0	0.0	0.0	132.0
Poultry litter production	3203.6	0.0	1601.8	0.0	0.0	0.0	1601.8
Seed	918.7	1295.2	1167.1	0.0	0.0	697.0	1359.4
Transportation of inputs	13.0	48.7	86.4	0.0	0.0	10.8	52.9
Equipment	179.7	175.3	148.3	0.0	0.0	0.0	167.8
Drying	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labor	84.1	76.5	54.4	0.0	0.0	0.0	71.7
Diesel fuel	3541.8	3210.9	2781.6	0.0	0.0	0.0	3178.1

Total energy (MJ ha^{-1} yr^{-1})	**8204.9**	**4806.7**	**5971.6**	**0.0**	**0.0**	**707.8**	**6563.7**
Greenhouse gas emissions analysis							**kg CO_2e ha^{-1} yr^{-1}**
Poultry litter transport	22.5	0.0	11.3	0.0	0.0	0.0	11.3
Poultry litter production	123.7	0.0	61.8	0.0	0.0	0.0	61.8
Seed	77.2	68.9	53.8	0.0	0.0	34.9	78.2
Transportation of inputs	1.0	3.8	6.8	0.0	0.0	0.8	4.1
Equipment	11.7	11.4	9.6	0.0	0.0	0.0	10.9
Drying	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Diesel fuel	254.6	230.8	199.9	0.0	0.0	0.0	228.4
N2O - manure application	667.3	0.0	333.7	0.0	0.0	0.0	333.7
N2O - aboveground crop residues, direct	281.7	130.1	108.2	0.0	0.0	0.0	173.3
N2O - belowground crop residues, direct	138.2	41.0	61.3	0.0	0.0	0.0	80.2
N2O - aboveground crop residues, indirect	63.4	29.3	24.3	0.0	0.0	0.0	39.0
N2O - belowground crop residues, indirect	31.1	9.2	13.8	0.0	0.0	0.0	18.0
N2O - total from crop residue	514.4	209.6	207.6	0.0	0.0	0.0	310.5
Total GHG (kg CO_2e ha^{-1} yr^{-1})	**1672.4**	**524.5**	**884.4**	**0.0**	**0.0**	**35.7**	**1039.0**

Table B11: Emergy table for a three-year organic IWG-red clover polyculture in central New York.

Inputs	**Unit**	**Quantity**	**UEV (sej/g or sej/J)**	**Emergy Flow (sej ha^{-1} yr^{-1})**
IWG Seed	g	1.68E+04	1.45E+09[1]	8.13E+12
Clover Seed	g	2.24E+04	1.45E+09[1]	3.25E+13
Fertilizer (manure)	g	5.38E+06	2.13E+08[1]	3.82E+14
Labor	J	3.39E+07	1.24E+07[2]	1.40E+14
Machinery - grain	g	1.20E+04	1.13E+10[2]	4.51E+13
Machinery - forage	g	1.25E+04	1.13E+10[2]	4.71E+13
Fuel	J	1.09E+09	1.10E+05[3]	3.99E+13
Rain	J	1.43E+11	3.10E+04[4]	1.48E+15
Sun	J	1.23E+14	1.00E+00[5]	4.11E+13
Wind	J	6.04E+10	2.45E+03[6]	4.93E+13
Soil Erosion	J	6.80E+09	1.24E+05[7]	2.81E+14

Fraction	**Year 1**	**Year 2**	**Year 3**	**Total**
Renewable Local	1.57E+15	1.57E+15	1.57E+15	4.70E+15
Nonrenewable Local	6.01E+14	1.21E+14	1.21E+14	8.43E+14
Purchased - grain	6.89E+14	4.53E+14	4.21E+14	1.56E+15
Purchased - forage	7.42E+14	4.63E+14	4.31E+14	1.64E+15
Emergy Yield - grain	2.86E+15	2.14E+15	2.11E+15	7.11E+15
Emergy Yield - forage	2.91E+15	2.15E+15	2.12E+15	7.18E+15

Outputs	**Unit**	**Quantity**	**Specific Emergy (sej g-1)**
Grain Yield	g	1.91E+06	3.71E+09
Forage Yield	g	2.13E+07	3.37E+08

[1]Coppola et al. 2009; [2]Brandt-Williams 2002; [3]Odum 1996; [4]Brown & Ulgiati 2004; [5]Odum 1986; [6]Brown & Ulgiati 2002; [7]Pulselli et al. 2007

Table B12: Emergy table for a three-year continuous organic IWG monoculture in central New York.

Inputs	Unit	Quantity	UEV (sej/g or sej/J)	Emergy Flow (sej ha^{-1} yr^{-1})
Kernza Seed	g	1.68E+04	1.45E+09[1]	2.44E+13
Fertilizer (manure)	g	5.38E+06	2.13E+08[1]	3.82E+14
Labor	J	3.39E+07	1.24E+07[2]	1.40E+14
Machinery - grain	g	1.20E+04	1.13E+10[2]	4.51E+13
Machinery - forage	g	1.25E+04	1.13E+10[2]	4.71E+13
Fuel	J	1.09E+09	1.10E+05[3]	3.99E+13
Rain	J	1.43E+11	3.10E+04[4]	1.48E+15
Sun	J	1.23E+14	1.00E+00[5]	4.11E+13
Wind	J	6.04E+10	2.45E+03[6]	4.93E+13
Soil Erosion	J	6.80E+09	1.24E+05[7]	2.81E+14
Fraction	**Year 1**	**Year 2**	**Year 3**	**Total**
Renewable	1.57E+15	1.57E+15	1.57E+15	4.70E+15
Nonrenewable Local	6.01E+14	1.21E+14	1.21E+14	8.43E+14
Purchased - grain	5.30E+14	4.21E+14	4.21E+14	1.37E+15
Purchased - forage	5.40E+14	4.31E+14	4.31E+14	1.40E+15
Total Emergy Yield - grain	2.70E+15	2.11E+15	2.11E+15	6.92E+15
Total Emergy Yield - forage	2.71E+15	2.12E+15	2.12E+15	6.95E+15
Outputs	**Unit**	**Quantity**	**Specific Emergy (sej g-1)**	
Grain Yield	g	1.95E+06	3.54E+09	
Forage Yield	g	1.69E+07	4.12E+08	

[1]Coppola et al. 2009; [2]Brandt-Williams 2002; [3]Odum 1996; [4]Brown & Ulgiati 2004; [5]Odum 1986; [6]Brown & Ulgiati 2002; [7]Pulselli et al. 2007

Table B13: Emergy table for a three-year continuous organic hard red winter wheat-red clover polyculture in central New York.

Inputs	**Unit**	**Quantity**	**UEV (sej/g or sej/J)**	**Emergy Flow (sej ha^{-1} yr^{-1})**
Wheat Seed	g	1.08E+05	1.45E+09[1]	1.56E+14
Clover Seed	g	2.24E+04	1.45E+09[1]	3.25E+13
Fertilizer (manure)	g	1.79E+06	2.13E+08[1]	3.82E+14
Labor	J	1.61E+07	1.24E+07[2]	2.00E+14
Machinery - grain	g	7.21E+03	1.13E+10[2]	8.15E+13
Machinery - forage	g	7.39E+03	1.13E+10[2]	8.35E+13
Fuel	J	5.64E+08	1.10E+05[3]	6.20E+13
Rain	J	4.77E+10	3.10E+04[4]	1.48E+15
Sun	J	4.11E+13	1.00E+00[5]	4.11E+13
Wind	J	2.01E+10	2.45E+03[6]	4.93E+13
Soil Erosion	J	7.57E+09	1.24E+05[7]	9.39E+14

Fraction	**Year 1**	**Year 2**	**Year 3**	**Total**
Renewable Local	1.57E+15	1.57E+15	1.57E+15	4.70E+15
Nonrenewable Local	9.39E+14	9.39E+14	9.39E+14	2.82E+15
Purchased - grain	9.14E+14	9.14E+14	9.14E+14	2.74E+15
Purchased - straw	9.16E+14	9.16E+14	9.16E+14	2.75E+15
Emergy Yield - grain	3.42E+15	3.42E+15	3.42E+15	1.03E+16
Emergy Yield - straw	3.42E+15	3.42E+15	3.42E+15	1.03E+16

Outputs	**Unit**	**Quantity**	**Specific Emergy (sej g-1)**
Grain Yield	g	9.41E+06	1.09E+09
Straw Yield	g	1.32E+07	7.78E+08

[1]Coppola et al. 2009; [2]Brandt-Williams 2002; [3]Odum 1996; [4]Brown & Ulgiati 2004; [5]Odum 1986; [6]Brown & Ulgiati 2002; [7]Pulselli et al. 2007

Table B14: Emergy table for a three-year continuous organic hard red winter wheat monoculture in central New York.

Inputs	**Unit**	**Quantity**	**UEV (sej/g or sej/J)**	**Emergy Flow (sej ha^{-1} yr^{-1})**
Wheat Seed	g	1.08E+05	1.45E+09[1]	1.56E+14
Fertilizer (manure)	g	1.79E+06	2.13E+08[1]	3.82E+14
Labor	J	1.61E+07	1.24E+07[2]	2.00E+14
Machinery - grain	g	7.21E+03	1.13E+10[2]	8.15E+13
Machinery - forage	g	7.39E+03	1.13E+10[2]	8.35E+13
Fuel	J	5.64E+08	1.10E+05[3]	6.20E+13
Rain	J	4.77E+10	3.10E+04[4]	1.48E+15
Sun	J	4.11E+13	1.00E+00[5]	4.11E+13
Wind	J	2.01E+10	2.45E+03[6]	4.93E+13
Soil Erosion	J	7.57E+09	1.24E+05[7]	9.39E+14

Fraction	**Year 1**	**Year 2**	**Year 3**	**Total**
Renewable Local	1.57E+15	1.57E+15	1.57E+15	4.70E+15
Nonrenewable Local	9.39E+14	9.39E+14	9.39E+14	2.82E+15
Purchased - grain	8.82E+14	8.82E+14	8.82E+14	2.64E+15
Purchased - straw	8.84E+14	8.84E+14	8.84E+14	2.65E+15
Emergy Yield - grain	3.39E+15	3.39E+15	3.39E+15	1.02E+16
Emergy Yield - straw	3.39E+15	3.39E+15	3.39E+15	1.02E+16

Outputs	**Unit**	**Quantity**	**Specific Emergy (sej g-1)**
Grain Yield	g	8.19E+06	1.24E+09
Straw Yield	g	1.21E+07	8.44E+08

[1]Coppola et al. 2009; [2]Brandt-Williams 2002; [3]Odum 1996; [4]Brown & Ulgiati 2004; [5]Odum 1986; [6]Brown & Ulgiati 2002; [7]Pulselli et al. 2007

Table B15: Emergy table for a three-year organic corn-soybean-spelt rotation in central New York.

Inputs	**Unit**	**Quantity**	**UEV (sej/g or sej/J)**	**Emergy Flow (sej ha^{-1} yr^{-1})**
Corn seed	g	2.03E+04	8.67E+08[1]	1.76E+13
Soybean seed	g	7.61E+04	1.82E+09[2]	1.39E+14
Spelt seed	g	1.35E+05	1.45E+09[3]	1.96E+14
Clover Seed	g	1.68E+04	1.45E+09[3]	2.44E+13
Fertilizer (manure)	g	3.00E+06	2.13E+08[3]	6.39E+14
Labor	J	3.19E+07	1.24E+07[4]	3.96E+14
Machinery - grain	g	2.11E+04	1.13E+10[4]	2.39E+14
Fuel	J	1.16E+09	1.10E+05[5]	1.28E+14
Rain	J	4.77E+10	3.10E+04[6]	1.48E+15
Sun	J	4.11E+13	1.00E+00[7]	4.11E+13
Wind	J	2.01E+10	2.45E+03[8]	4.93E+13
Soil Erosion	J	7.57E+09	1.24E+05[9]	9.39E+14
Fraction	**Year 1**	**Year 2**	**Year 3**	**Total**
Renewable Local	1.57E+15	1.57E+15	1.57E+15	4.70E+15
Nonrenewable Local	9.39E+14	9.39E+14	9.39E+14	2.82E+15
Purchased - grain	4.85E+14	6.06E+14	6.87E+14	1.78E+15
Emergy Yield - grain	2.99E+15	3.11E+15	3.19E+15	9.30E+15
Outputs	**Unit**	**Quantity**	**Specific Emergy (sej g-1)**	
Grain Yield	g	1.60E+07	5.82E+08	

[1]Rótolo et al. 2015; [2]Castellini et al. 2006; [3]Coppola et al. 2009; [4]Brandt-Williams 2002; [5]Odum 1996; [6]Brown & Ulgiati 2004; [7]Odum 1986; [8]Brown & Ulgiati 2002; [9]Pulselli et al. 2007

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