Effects of High Intensity Management of Winter Wheat on Grain Yield, Straw Yield, Grain Quality, and Economic Returns

Thesis

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By

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Abstract

Many farmers typically regard wheat as a “low input” crop and expect low yields and low returns. Conversely, some farmers intensively manage wheat with many inputs and expect high yields and returns. The objective of this research was to identify inputs that improve wheat grain yield, straw yield, and economic return and reduce deoxynivalenol (DON) concentration in the grain. An incomplete factorial, omission trial was established at two locations in Ohio (South Charleston and Custar) during the 2019-2020 and 2020-2021 growing seasons. Treatments consisted of intensive management (IM) which received all inputs, a traditional management (TM), and the individual addition or removal each input from the TM or IM, respectively. The inputs were a high seeding rate, a high N rate, a split application of N, a spring sulfur application, a fungicide application at Feekes 9, and a fungicide application at Feekes 10.5.1. Intensive management increased grain yield at three of the site-years during this study by an average of 0.83 Mg ha^{-1}. At the South Charleston location, in general, the use of a fungicide at either timing proved to be important for protecting yield. The addition of a fungicide at Feekes 10.5.1 to the TM significantly protected yield both years by an average of 0.66 Mg ha^{-1} and the removal of this fungicide from the IM significantly decreased yield by 0.63 Mg ha^{-1} in 2021. Additionally, at the same location the addition of a fungicide at Feekes 9 to the TM and the removal of a fungicide from the IM significantly changed yield in 2020 by 0.81 and -0.71 Mg ha^{-1}. At Custar, only one treatment significantly changed yield in either year. In 2021, the removal of split N from the IM significantly reduced grain yield by 0.44 Mg ha^{-1}. Straw yield was not consistently affected by any treatment in this study. DON concentration was significantly reduced by the IM

at South Charleston both years due to the addition of a fungicide at Feekes 10.5.1. Intensive management did not increase partial economic returns at any site-year during this study and individual treatment affects were inconsistent. These results suggest that although IM has can improve grain yield and quality it fails to do so economically at the prices used in this study.

Dedication

Dedicated to my parents. Bob and Lisa Peterson.

Acknowledgments

When I initially enrolled at Ohio State, graduate school was not even a thought in my head but my mom encouraged me to explore the idea. So I would like to start by thanking her for urging me to attend gad school even when I told her I didn't want to. She is always helping me to become the best version of myself and I wouldn't be where I am today without her. I would also like to recognize my dad for showing me how to work hard, care for others, and teaching me to "quit complaining, and find a solution." Thank you to my oldest sister Sarah and her husband John for giving me a place to stay on my many trips to northwest Ohio and showing me that Dietsch's is the best way to cool off after a long day at the Northwest research station. Thank you to my sister Hannah for supporting me throughout graduate school and always being interested in hearing about my project. Finally, thank you to my whole family for coming through on the last minute to help me complete my field work before a coming storm or a statewide lockdown to ensure my project could be successfully completed.

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Chapter 1. Literature Review

1.1. Wheat History and Use in the United States and Ohio

In the U.S. and around the world, wheat (*Triticum aestivum* L.) is a vital food crop. Products made from wheat represent a large part of diets worldwide with one survey in the U.K. finding that one-third of all energy consumed by the average adult came from wheat (Shewry and Hey, 2015). In the U.S. wheat is divided into six classes: hard red spring wheat, hard red winter wheat, soft red winter wheat (SRW), soft white wheat, hard white wheat, and durum wheat (Triticum durum Desf.) (USDA GIPSA, 2014).

Each class of wheat is grown in a different geographic region and is best suited for a specific use due to different protein and gluten content, milling quality, and other characteristics (Wheat Foods Council, 2019). Durum wheat is grown in the Northern Plains and is ideal for pasta (Wheat Foods Council, 2019; NAWG, 2020). Hard red wheat, both winter and spring, is grown across the Great Plains and is used in breads (Wheat Foods Council, 2019; NAWG, 2020). Soft white wheat, used for cakes and pastries, is typically grown in the Pacific Northwest and some parts of Michigan and New York (Wheat Foods Council, 2019; NAWG, 2020). Hard white wheat is a relatively new class, which is grown sparsely across the country and used for Asian noodles and flat breads (Wheat Foods Council, 2019; NAWG, 2020). Finally, SRW is used for cookies and crackers and is predominately grown east of the Mississippi River (Wheat Foods Council, 2019; NAWG, 2020). Ohio is consistently one of the top SRW wheat producing states, producing more than 585,133 Mg of wheat in 2019, and is home to one of the largest wheat flour mills in North America (US Wheat Associates, 2019; USDA NASS, 2020a; "Milling Statistics," 2020).

Over the last 20 years, Ohio farmers have chosen to plant less and less wheat. In 2000, Ohio farmers planted 445,154 ha of winter wheat, according to the USDA National Agricultural Statistics Service (NASS) (USDA NASS, 2020a). In 2010, the planted area had fallen to 291,373 hectares and for the 2020 harvest, Ohio farmers only planted 226,624 hectares (USDA NASS, 2020a). Farmers are likely decreasing wheat production because wheat has consistently produced a low or negative return on investment (ROI), especially when compared to other crops such as maize (*Zea mays* L.) or soybean (*Glycine max* L. Merrill) (Gillespie, 2019). In 1998, the USDA estimated the net returns for wheat in the Midwest at -\$163.02 ha^{-1} and by 2018 net returns had fallen to -\$266.76 per hectare (Gillespie, 2019). When compared to the net returns for corn during the same time, which returned -\$229.71 and -\$69.16 in 1998 and 2018 respectively, it becomes clear why recently farmers are planting less wheat, it's less profitable (Gillespie, 2019). In addition, other management challenges such as planting and harvesting at different times than corn and soybean have likely made wheat a less desirable crop for farmers. Similarly, pest management strategies are different. These factors result in increased management cost for the farmer and have likely contributed to the decrease in the number of hectares being planted into wheat each year in Ohio (Gillespie, 2019).

However, wheat provides a number of short- and long-term benefits that are not easily factored into an economic analysis of the crop's performance. Primarily, wheat as a cash crop, if raised profitably, can diversify the farmers' income sources and places less reliance on the corn and soybean markets. In addition, planting wheat may also provide a new source of income beyond just the grain, namely the farmer can sell the straw, further diversifying their income. Furthermore, research has shown that soybean yields can increase as much as 5% when wheat is included in the crop rotation (Huo et al., 2020). Fall planted crops, such as wheat, provide numerous soil health, water quality, and environmental benefits. They can improve biological activity, reduce soil erosion, and increase aggregate stability. As a result, fall planted crops can reduce particulate bound P runoff and nitrate leaching (Martinez and Guiraud, 1990; Mutchler and McDowell, 1990; Cook, 1992; Alliaume et al., 2014; Moore et al., 2014; Finney et al., 2017; Rorick and Kladivko, 2017; Thom et al., 2018; Quinn and Steinke, 2019). Similarly, as a fall planted crop, wheat can provide the opportunity to double or relay-inter crop, meaning farmers can harvest two cash crops during a single year (Shrestha et al., 2021). Many of these benefits are hard to put a dollar value on, meaning farmers typically do not account for them when making cropping decisions. Clearly, wheat can provide numerous benefits to the farmer, but ultimately, the crop will not be planted unless it is sufficiently profitable.

1.2. Wheat Biology and Cultivation in Ohio

The wheat grown in Ohio is most commonly SRW wheat which is a winter annual crop, meaning it is planted in the fall, overwinters, and is harvested the following summer (Lindsey et al., 2017; USDA NASS, 2020). In Ohio, wheat is planted following the harvest of the preceding crop and after the risk of an infestation from Hessian fly (*Mayetiola destructor*) is reduced due to cooler weather (Chen, Foster, Taylor, and Araya, 1990; Buntin, Ott, and Johnson, 1992). This results in a typical planting date for wheat of late September in northern Ohio and early October in southern Ohio (Lindsey et al., 2017a). The Hessian fly can be major pests targeting wheat if precautions are not taken. In the fall, larvae infests the young plant damaging tillers and in the spring it infests the stem and reduces grain fill (Buntin et al., 1992). Weed control is primarily performed with competition from the wheat seeded at a high density and by selecting a field with a low weed seed bank, but can be supplemented with herbicides (Anderson and Impiglia, 2002). After planting, the wheat seed will germinate and emerge from the ground, which is the growth stage Feekes 1 (Miller, 1992; Lindsey, Paul, and Lentz, 2017b). After emergence, the young plant will produce many secondary shoots known as tillers during Feekes stages 2-3, but before the wheat can mature it must go through vernalization (Lindsey et al., 2017b). Vernalization is genetic control that requires the plant to undergo a specific length of time, depending on variety, at or near freezing before the plant is able to transition to reproductive growth (Brooking, 1996; Acevedo, Silva, and Silva, 2002).

In the spring, once vernalization is complete the plant begins to grow again and continues to produce new tillers before beginning vertical growth (Feekes 4-5) (Lindsey et al., 2017b). This period of early spring growth is typically when nitrogen fertilizer is applied in Ohio and is one of the last chances to control weeds (Lindsey et al., 2017b). As vertical growth continues, the stem begins to elongate and eventually the first node rises above the soil surface signifying the start of jointing (Feekes 6) (Lindsey et al., 2017b). As growth continues, the second node will rise above the soil surface (Feekes 7) followed by the tip of the final leaf, known as the flag leaf, becoming visible (Feekes 8) (Lindsey et al., 2017b). The flag leaf provides the majority of the photosynthetic energy for further grain development and when the ligule is fully emerged, the plant has reached the Feekes 9 growth stage (Lindsey et al., 2017b). At this time, the spike begins to grow inside the stem and is considered to be in the "boot stage" (Feekes 10). A fungicide application at or just before the "boot stage" may be warranted to protect the flag leaf and upper leaves from foliar disease to ensure adequate grain fill and maximum yield (Cook, Hims and Vaugh, 1999; Lindsey et al., 2017b).

After Feekes 10, decimals are used to further delineate growth and maturity of the wheat plant. Feekes 10.1 corresponds with the awns and spike beginning to emerge and each 0.1 advancement in Feekes stage corresponds with a ¼ emergence of the spike (Lindsey et al., 2017b). At Feekes 10.5, the spike is fully emerged and anthesis begins at Feekes 10.5.1 with the anthers emerging first in the center of the spike and then moving to the tip (Feekes 10.5.2) before finishing emergence at the base (Feekes 10.5.3) (Acevedo et al., 2002; Lindsey et al., 2017b). During flowering, Fusarium Head Blight (FHB) (commonly caused by *Fusarium graminearum*) can be an issue so a fungicide application may be needed to control the disease (Yoshida et al., 2011; Lindsey et al., 2017b). After anthesis begins the grain filling period starting with watery ripe (Feekes 10.5.4) and then milky ripe kernels (Feekes 11.1) (Lindsey et al., 2017b). Once the grain is filled, the dry down process begins first with doughy or mealy ripe kernels (Feekes 11.2) before the kernels begin to harden at Feekes 11.3 and finally are mature and harvest ready at Feekes 11.4 (Lindsey et al., 2017b). Wheat harvest in Ohio typically occurs around late June or early July when the grain reaches 13 to 15% moisture concentration (US Wheat Associates, 2019). Following harvest, the farmer may choose to collect and bale the wheat straw to be sold for animal bedding, ground cover, and more. After the wheat straw has been collected, the farmer may decide to fallow the ground, plant a cover crop, or a second cash crop such as soybean.

1.3. Wheat Seeding Rate

Wheat seeding rate is one of the most important and easiest factors for farmers to control. Seeding rate plays a major role in determining the maximum yield potential of a wheat crop. The three factors that contribute to wheat grain yield are: heads per unit area, kernels per head, average weight per kernel (Frederick and Marshall, 1985a; Joseph et al., 1985a). Seeding rate plays a crucial role in determining the number of productive tillers per unit area, which produce heads upon maturity, therefore seeding rate contributes to the number of heads per unit area which impacts yield (Joseph et al., 1985a). Although the plant can adapt to variations in seeding rate to maintain yield by increasing tillering at low populations and decreasing tillering at high populations there is a limit to the number of tillers a single plant can produce (Joseph et al., 1985a). Therefore in order to maximize heads per unit area then seeding rate must optimized (Frederick and Marshall, 1985a; Joseph et al., 1985a).

The optimal seeding rate has long been studied, but one unifying seeding rate has not been found because the optimal seeding rate is highly dependent on environment conditions and management decisions (Roth et al., 1984; Marshall and Ohm, 1987; Geleta et al., 2002a). In 1984, Roth et al. (1984) found that wheat yield increased as seeding rate increased from 100 to 235 kg ha^{-1} (approximately 278 to 653 seeds/m^2) but as seeding rate increased, so did lodging leading to the conclusion that a seeding rate of 168 kg ha^{-1} (467 seeds/m^2) was ideal. Researchers in Virginia, USA found that in 1981 and 1982, when planting in narrow rows (10 cm) the

optimal seeding rate was between 101 and 134 kg ha^{-1}, which is equivalent to 283 to 376 seeds per m^2, for the variety they tested (Joseph et al., 1985a). Similarly, in Nebraska, USA researchers found that based on their response curve, a seeding rate between 65 kg ha^{-1} and 130 kg ha^{-1} was the recommended range and a seeding rate of 118 kg ha^{-1} was the agronomically optimum seeding rate (AOSR) (Geleta et al., 2002a). Lollato et al. (2019) analyzed data on management practices used by farmers in the Kansas Wheat Yield Contest and found that yield was not affected by seeding rate until it exceeded 305 seeds per m^2 and then it decreased by 2.7 Mg ha^{-1} for every increase of
100 seeds m^{-2}.

These results correspond with the historically recommended seeding rate of around 300 seeds per m^2 but recently some have suggested that new cultivars may be better adapted to higher seeding rates (Lindsey et al., 2017a, 2020). Recently, researchers in Kansas, USA found that across a two-year study, an increased seeding rate of 400 seeds per m^2 increased grain yield in a no-till system by 0.4 Mg ha^{-1} when compared to the recommended seeding rate of 278 seeds m^{-2}, but found that it did not improve profitability (Jaenisch et al., 2019). Likewise a recent study in Ohio found that the AOSR for four modern cultivars was between 350 and 500 seeds m^{-2} and the economic optimum seeding rate (EOSR) was about 100 seeds m^{-2} lower than the AOSR (Lindsey et al., 2020). The variations in optimal seeding rate can likely be attributed to variation in planting date, environmental factors, cultivar, soil, and fertility, and much more. These results suggest that the AOSR for modern cultivars may be higher than previously reported, although the extra seed does not result in a better economic return.

1.4. Nitrogen Fertilizer

Nitrogen (N) is one of the most carefully managed nutrients in crop production and plays an important role in many plant functions. Nitrogen is a vital component of countless organic molecules in the plant, ranging from amino acids and proteins to chlorophyll and much more (Fageria, 2009). As such, the application of N fertilizer is an important component of small grains production, but over application can negatively affect quality parameters and the environment. Over application of N fertilizer can lead to detrimental effects such as lodging and increased disease (Olesen et al., 2003; Brown and Petrie, 2006; Salgado et al., 2017). Therefore, application of the right amount of nitrogen fertilizer is critical to prevent excess cost, quality issues, and environmental damage while still maximizing yield.

Numerous studies have been performed to identify the optimal N rate. This is complicated by the fact that the optimal rate of N is dependent on a number of parameters, such as climate conditions, availability of soil N prior to fertilization, and other farmer controlled factors (Zhen-Ling' et al., 2006). Chinese researchers found that across 5 sites with low initial soil N, the optimal N fertilizer rate was 90 kg-N ha^{-1} (Zhen-Ling' et al., 2006). Researchers in Italy found that during the 2004 and 2005 growing season the optimal nitrogen rate for emmer (*Triticum dicoccum*), a predecessor to modern wheat, was between 60 and 90 kg N ha^{-1} (Marino et al., 2009). On the other hand, Camara, Payne, and Rasmussen found no significant difference between N fertilization rate of 90 kg N ha^{-1} and 135 kg N ha^{-1} (Camara et al., 2003). In 1992, researchers in South Dakota, USA reported the optimal rate of N fertilization to be around 110 kg N ha^{-1} (Woodard and Bly, 1998). These studies suggest that the optimal nitrogen fertilization rate for soils with low soil N is around 100 kg N ha^{-1}. Which is in line with the most recent version of the Tri-State Fertilizer Guide which recommends between 80 and 130 kg N ha^{-1} depending on yield potential(Culman et al., 2020).

The efficacy of N fertilizer is affected by more than just application rate, but also application timing. Weisz, Crozier, and Heiniger (2001) found that the maximum crop uptake of N occurred during tillering, just before jointing (Feekes stage 3-5). They recommended applying nitrogen at Zadok's Growth Stage 25 (GS25, equivalent to Feekes 3) if tiller count was <550 per m^2 and there was no risk of freezing, otherwise nitrogen should be applied at GS30 (Feekes 5) (Weisz et al., 2001). Similarly, researchers in Virginia, USA found that the optimal N timing was just after GS30 in a full tillage cropping system (Baethgen and Alley, 1989). In Iran, it was found that application during vegetative stages, specifically just before tillering, resulted in the most yield (Abedi et al., 2011). Researchers in Idaho, USA found that there was no difference between topdress N application in the fall during seeding or spring during tillering in an irrigated HRW wheat system (Brown and Petrie, 2006). They also found that late season (Feekes 10.2-10.5) N application did not improve yield which they attributed to increased lodging from the overapplication of N fertilizer (Brown and Petrie, 2006).The results of these studies support the recommendations found in the Ohio Agronomy Guide 15th edition which says the optimal timing for N application is between "green-up" (Feekes 3) and jointing (Feekes 6).

1.5. Sulfur Fertilizer

Sulfur (S) is an important macronutrient that plays a major role in crop growth and development. It is required for the production of a number of amino acids and therefore, is vital for protein production (Chen et al., 2005; Fageria, 2009). It is also crucial for the production of chlorophyll and nitrogenase (Fageria, 2009). For many years, deposition of atmospheric S has been enough to meet crop needs but due to regulations aimed at reducing pollution, the amount of S being released into the air has decreased and atmospheric deposition of sulfur has fallen dramatically in Ohio and the Eastern United States (US EPA, 2019). In 2000, >20 kg-S ha^{-1} were deposited in Ohio, but by 2018, atmospheric deposition has fallen to 5 kg-S/ha (US EPA, 2019). This is below crops uptake of around 6.7 kg ha^{-1} for a 5 Mg ha^{-1} wheat crop and as a result, sulfur deficiency may occur without the application of fertilizer (Culman et al., 2019).

Soil S levels are a function of soil S mineralization and weathering, aerial S deposition, S fertilizer additions, S leaching, and crop removal (Dick, Kost, and Chen, 2015). Mineralization is the process of converting organically bound S into inorganic plant available S, which is done mostly by microbial activity (Eriksen, 2015; Schoenau and Malhi, 2015). Therefore, the factors that influence microbial activity have a large influence on S mineralization (Eriksen, 2015). Factors such as temperature, moisture, pH and most importantly the carbon-sulfur (C/S) ratio of the soil (Eriksen, 2015; Schoenau and Malhi, 2015). Sulfur mineralization is greatest when soils are near field capacity and around 35° C (Schoenau and Malhi, 2015). C/S ratios of >400:1 normally result in the organic sulfur being bound to soil particles and becoming unavailable to plants but C/S ratios of <200:1 typically result in an increase in plant available S (Schoenau and Malhi, 2015). Weathering is the reduction and or oxidation of inorganic forms of sulfur (Schoenau and Malhi, 2015). Weathering can result in a decrease in plant available S by in some situations, reducing inorganic S to sulfate salts or it can increase plant available S by oxidizing reduced forms of S fertilizer like elemental S (Schoenau and Malhi, 2015). Leaching of S occurs when water percolates down through the soil and carries the S in solution with it (Dick et al., 2015). Leaching is influenced by factors that increase movement of water through the soil such as precipitation, soil texture, and soil adsorption (Dick et al., 2015). Soil texture effects the speed at which water moves through the soil profile as such course soils will have more leaching and fine soils will have less leaching (Dick et al., 2015). Soil adsorption is the binding of sulfate ions to the soil and reduces leaching (Dick et al., 2015). Adsorption of S is influenced by soil pH (occurring mostly in low pH environments) and other ions which may bind more tightly to the soil and may replace S ions (Dick et al., 2015). Overall, plant available S is influenced by many environmental, landscape, and cultural factors.

Early research suggested that the application of a sulfur fertilizer does not improve crop yield. In 1992, researchers in Kansas, USA found that the application of sulfur did not increase wheat grain or forage yield, but did improve early harvested forage quality (Feyh and Lamond, 1992). The researchers attributed this to the fine textured silt loam soil of this experiment because previous research had shown that sulfur fertilizer only produced a yield increase in course textured soils (Feyh and Lamond, 1992). Similarly, researchers in Southern Illinois, USA found that sulfur fertilizer did not increase yield regardless of tillage practices or variety. This was likely due to the high levels of extractable S in the soil surface, as well, as adequate sulfur deposition from rainfall (Sawyer and Ebelhar, 1995). These research projects were performed prior to the reduction in atmospheric deposition, so their results are as expected. Newer research, performed after the reduction in atmospheric deposition, has shown that wheat yield can be improved through the application of sulfur. Researchers in Oklahoma, USA found that both wheat grain and forage yield was improved through the application of a sulfur fertilizer and that the type of sulfur fertilizer was important with $CaSO_4$ performing better than elemental S (Girma et al., 2005). Similarly, in 2019, researchers in Kansas, USA found that the addition of a sulfur fertilizer increased winter wheat grain yield by 0.3 Mg Ha^{-1} across 2 years in a no-till location (Jaenisch et al., 2019).

1.6. Foliar Fungicide

Throughout the season, wheat is susceptible to a number of different fungal diseases that can reduce crop growth and yield. Fungal diseases, such as FHB, a number of wheat rusts, caused by a multiple pathogens in the *Puccinia* genus, Take-All, caused by *Gaeumannomyces graminis* var. *tritici*, and many more are common throughout Ohio (James Cook, 2003; Paul et al., 2005; Salgado et al., 2016; Lindsey et al., 2017a). These diseases can be effectively controlled with a suitable integrated pest management (IPM) program.

Cultural practices are the foundation of an IPM program and work to reduce and prevent the spread of crop diseases (Hahn et al., 2016; UC Davis,). For example, farmers can remove non-crop disease hosts, such as grass weeds, in and around their field to reduce the spread disease pathogens to the crop (Roelfs et al., 1992; Lindsey et al., 2017a; ADHB, 2019). Similarly, excessive nitrogen application can lead to increased severity of foliar diseases, such as leaf rust (caused by *Puccinia recondita f. sp. tritici*). Therefore, farmers should carefully manage their fertility levels as part of an IPM program (Simón et al., 2011; Salgado et al., 2016; Lindsey et al., 2017a; ADHB, 2019; Ghadamkheir et al., 2020). In order to control wheat diseases, the most important and cost effective cultural practice a farmer can implement is to plant resistant cultivars (Roelfs et al., 1992; Lindsey et al., 2017a; ADHB, 2019). In addition, a crop rotation of two or more years between planting wheat is recommended to reduce pathogen levels in a field (Simón et al., 2011; Lindsey et al., 2017a; ADHB, 2019).

As a complement to cultural practices, producers may choose to use mechanical methods, namely tillage, to reduce disease populations of pathogens that survive on crop residue (Lindsey et al., 2017a). Sutton and Vyn (1990) found that tillage will promote the breakdown of crop residue and in a continuous wheat rotation can reduce disease incidence of certain foliar diseases. If the above methods fail to provide adequate control of fungal wheat diseases, the use of a fungicide may be warranted. Fungicides can be used as a seed treatment or applied as a foliar application (Bai and Shaner, 1994). Fungicidal seed treatments can control early seedling diseases but are ineffective at controlling fungal diseases later in the season (Christ, 1988; Bai and Shaner, 1994). To control fungal disease later in the season, a foliar fungicide may be necessary (Wegulo et al., 2011; Lindsey et al., 2017a; ADHB, 2019).

Timing of a fungicide application is partially determined by the objective of the application. If the goal is to prevent yield loss to disease alone, a fungicide should be applied prior to grain filling. Yield is highly related with green leaf area at the time of anthesis as such protecting this leaf area from damage caused by fungal infections is vital to high grain yields (Waggoner and Berger, 1986; Bryson et al., 1997; Gooding et al., 2000). The application of a fungicide is widely accepted as a method to protect green leaf area (Cook et al., 1999; Gooding et al., 2000; Willyerd et al., 2015). Cook et al. found that optimal spray timing was around GS39 (equivalent to Feekes 9), but applications as early as GS32 (Feekes 7) can be beneficial when disease pressure (incidence and severity) is high (Cook et al., 1999). Researchers at Kansas State University found that grain yield in a no till system was increased by 0.2 Mg ha^{-1} by the application of a fungicide at Feekes 6 and Feekes 11 (Jaenisch et al., 2019). The authors stated that "the absence of foliar fungicides reduced green canopy cover from approximately 84% to 39% at Belleville 2017, and similar trends were observed for the other locations" (Jaenisch et al., 2019). One study found that fungicide application improved yield by reducing plant energy expenditure in defense from fungal attack, but only improved yield if plant was under heavy disease pressure (Bertelsen et al., 2001). The authors also mentioned that strobilurin fungicides are suspected to delay leaf senescence even in the absence of fungal disease, but the mechanism is unknown (Bertelsen et al., 2001). In 2003, researchers found that fungal diseases decrease yield by promoting early senescence of upper leaves, which reduced grain fill and lowered test weight (Olesen et al., 2003).

Additionally, if the goal is to improve grain quality and yield it may be useful to apply the fungicide at anthesis. Proper timing can reduce the severity of disease and therefore improve quality parameters such as reducing deoxynivalenol (DON) content in the grain. Deoxynivalenol is a mycotoxin produced FHB (Rotter, 1996; Paul et al., 2018). DON causes a number of health problems in animals and humans (Rotter, 1996). Elevators in North America regularly test for DON and if found at a concentration higher than around 2.5 mg kg^{-1}, the grain may be rejected (Mennel Milling, 2019; NDM,). One method to reduce DON concentration in grain is to apply a fungicide (Yoshida et al., 2011; Paul et al., 2018). One group of researchers studying fungicide timing found that demethylation inhibitor fungicides applied at anthesis were most effective at reducing FHB and DON and that all application timing prevented yield loss from disease compared to the untreated control (Paul et al., 2018). These results align with the results of Yoshida et al. (2011) which found that fungicide application at anthesis reduced FHB and DON content and that a fungicide application 20 days after anthesis did not affect FHB, but it did reduce DON content (Yoshida et al., 2011). They also found that both a fungicide application at anthesis and 20 days after anthesis reduced DON content the most during both years of the study (Yoshida et al., 2011). Researchers in North Dakota found that, across five environments, fungicide application at flowering increased yield by reducing leaf rust and other leaf spots as well as controlling FHB at some locations (Ransom and McMullen, 2008). Similarly, Zhang et al. found that the application of a foliar fungicide improved yield by reducing the number of shriveled kernels from FHB and increased both kernel weight and kernels per spike (Zhang et al., 2010).

1.7. High Input Wheat Management

Traditionally, Ohio farmers grow wheat as a "low-input" crop and expect low grain yield and profit resulting in the crop having a bad reputation among farmers. However, in other parts of the country and internationally wheat is more closely managed with many inputs and can be higher yielding, leading to a potentially more profitable crop. Much of the research in high intensity wheat management has focused on increased fertilizer input and management, improved disease control, and increased seeding rates. Using a dataset developed from fields entered in the Kansas Wheat Yield Contest, one group of researchers developed models to identify which management decisions were most influential on high yielding wheat production (Lollato et al., 2019). Their models identified that the application of a foliar fungicide at flag leaf was the most important management practice affecting wheat yield due to a high number of wheat cultivars planted being susceptible to leaf and stripe rusts (Lollato et al., 2019). In addition, management decisions such as the use of in-furrow P fertilization, the adoption of no-tillage, and optimizing wheat seeding rate also played an important role in maximizing wheat yields (Lollato et al., 2019).

In Kentucky, USA, Knott, Van Sanford, Ritchey, and Swiggart investigated increased N rate and plant growth regulator (PGR) use in winter wheat production systems (Knott et al., 2016). They found that increased nitrogen rates above the current University of Kentucky recommendation of 112 kg-N ha^{-1} did not consistently increase yield and the use of a PGR did not significantly increase yield or change plant height, nor did a combination of increased N rate and a PGR result in improved yield (Knott et al., 2016). On the other hand, researchers in Michigan, USA found that the use of a PGR increased yield by approximately 5% when compared to the control, decreased plant height by greater than 5 cm, but nitrogen above the 84 kg-N ha^{-1} did not significantly increase yield (Swoish and Steinke, 2017).

Some claim that intensive management is not an additive process but instead multiplicative, so the total improvement from the combination is greater than the sum of the improvement from each input (Below, 2011; Henninger, 2012; Ruffo et al., 2015). To evaluate the validity of these claims researchers have utilized an “omission trial” experimental design. An omission trial utilizes two control treatments, one utilizing the high level for each input (HI) and one with the low level for each input (LI) (Bluck et al., 2015; Ruffo et al., 2015). The remaining treatments are the individual addition or removal of each input from the LI and HI controls respectively and each treatment is only compared to its respective control (Bluck et al., 2015; Ruffo et al., 2015; Jaenisch et al., 2019).

Quinn and Steinke (2019) utilized an omission trial to evaluate high input wheat management in Michigan; evaluating the use of urease inhibitors, nitrification inhibitors, PGR, fungicide, foliar micronutrients, and high N rates on both yield and economic returns (Quinn and Steinke, 2019). They found that the high input system did not significantly increase yield and due to the associated higher production cost resulted in a decreased net return (Quinn and Steinke, 2019). The authors attributed this result to a lack of adverse conditions during the site-years studied that would justify the extra inputs (Quinn and Steinke, 2019). In Kansas, USA researchers found slightly different results when evaluating the effects of additional N, S fertilizer, Chloride (Cl) fertilizer, high seeding rate, foliar fungicide, and a PGR (Jaenisch et al., 2019). The authors found that the high input system significantly increased yield but only improved returns in a scenario using a low cost fungicide and receiving a protein premium (Jaenisch et al., 2019). Additionally, there results showed that when yield limiting, adverse conditions were present the addition of certain inputs can improve yield but may not always increase profit (Jaenisch et al., 2019). Specifically, they found that foliar fungicides increased yield and were economical in high disease environments, high seeding rate increased yield and returns in no-tillage systems, and additional N and S fertilization increased yield in no-tillage systems but did not improve returns (Jaenisch et al., 2019).

Roth et al. in Wisconsin, USA took a slightly more nuanced approach and evaluated high, medium, and low input production systems (Roth et al., 2020). The low input system was modeled after farmer practices and had the lowest seeding rate and a single application of a low N rate; the medium input system increase the seeding rate, increased the N rate, split the N application, and added a foliar fungicide at Feekes 10.5.1 (Roth et al., 2020). The high input system received the same treatments as the medium system but further increased the seeding rate, further increased the N rate during two of the years of the study, received a PGR, added a foliar micronutrient and fungicide at Feekes 9, and added a micronutrient to the foliar fungicide at Feekes 10.5.1 (Roth et al., 2020). Their results show that as management intensity increased so did yield with an average across varieties of between a 1.11 to 1.35 Mg ha^{-1} increase in yield from the low input to high input system depending on the year (Roth et al., 2020). They also found that increased management led to higher profits with the middle management level producing the greatest profits followed by the high level and then the low level (Roth et al., 2020). Based on the results from these researchers, high input management systems have the potential to improve crop yield and profitability for Ohio farmers if properly studied and adapted to the growing conditions.

1.8. Summary

Although SRW wheat is an important crop and Ohio is one of the top producers, over the last few decades there has been a dramatic decrease in hectares of wheat planted in Ohio. Farmers are reducing the amount of wheat they are planting because it is not as profitable as other crops such as corn or soybean and imposes unique management challengers to the farmer.

However, wheat provides a number of soil health, pest control, and environmental benefits that are hard to factor into the farmer's economic analysis of a wheat crop. Wheat can be a profitable crop if managed correctly, but there is very little published research on high intensity management of SRW wheat, let alone research in Ohio. This project hopes to develop local recommendations for Ohio farmers on how to effectively manage their SRW wheat crop.

In Ohio, wheat is planted in the fall after the threat of Hessian fly has been reduced and is seeded at around 300-400 seeds per m^2. The wheat germinates and overwinters before resuming growth in the spring. Farmers will typically apply around 100 kg ha^{-1} of nitrogen and other nutrient fertilizers as needed at this time and perform any final weed control. In recent decades the atmospheric deposition of sulfur has been reduced, so it is likely that sulfur deficiencies will become more common and may warrant application of sulfur fertilizer. Another major concern for Ohio wheat growers is disease throughout the growing season, but specifically at the flag leaf and anthesis growth stages. As such, farmers should monitor crop conditions and be prepared to apply a fungicide as necessary. Proper management of wheat is a multifaceted process that can result in a crop that with a positive return on investment. The goals of this project are to 1) identify high input agronomic management techniques that can improve wheat grain yield, and 2) develop a return-on-investment (ROI) calculator to help farmers select inputs that maximize profitability.

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Chapter 2. High Intensity Management of Winter Wheat Increases Grain Yield but not Economic Returns

2.1. Abstract

Many farmers typically regard wheat as a “low input” crop and expect low yields and low returns. Conversely, some farmers intensively manage wheat with many inputs and expect high yields and returns. The objective of this research was to identify inputs that improve wheat grain yield, straw yield, and economic return and reduce deoxynivalenol (DON) concentration in the grain. An incomplete factorial, omission trial was established at two locations in Ohio (South Charleston and Custar) during the 2019-2020 and 2020-2021 growing seasons. Treatments consisted of intensive management (IM) which received all inputs, a traditional management (TM), and the individual addition or removal each input from the TM or IM, respectively. The inputs were a high seeding rate, a high N rate, a split application of N, a spring sulfur application, a fungicide application at Feekes 9, and a fungicide application at Feekes 10.5.1. Intensive management increased grain yield at three of the site-years during this study by an average of 0.83 Mg ha^{-1}. DON concentration was significantly reduced by the IM at South Charleston both years due to the addition of a fungicide at Feekes 10.5.1. Intensive management did not increase partial economic returns at any site-year during this study and individual treatment affects were rare and inconsistent. These results suggest that although IM has can improve grain yield and quality it fails to do so economically at the prices used in this study.

2.2. Introduction

In Ohio, wheat is the third most commonly planted annual row crop by area behind soybean (*Glycine max* L. Merrill) and corn (*Zea mays* L.) and the amount of land in Ohio planted to wheat has decreased by approximately 50% since 2000 (USDA NASS, 2020a, 2021). This is likely due to consistently low returns on investment (ROI), especially when compared to soybeans and corn (Gillespie, 2019). As such farmers in Ohio typically regard wheat as a "low input" crop and expect low yields and low returns (personal communication); however, some farmers take a different approach and intensively manage wheat with many inputs and expect high yields and returns.

Furthermore, wheat can provide the farmer with several benefits that are difficult to quantify when making cropping decisions. First, the inclusion of wheat diversifies the farmers income and places less reliance on the volatile corn and soybean markets while also providing a secondary revenue stream by selling the straw. Furthermore, as a fall planted crop, wheat provides the opportunity to double or relay-inter crop, meaning farmers can harvest two cash crops during a single year (Shrestha et al., 2021). Additionally, research has shown that including wheat in a crop rotation can increase the yield of the subsequent soybean crop by as much as 5% (Huo et al., 2020) and winter crops, such as wheat, can improve soil biological activity, reduce soil erosion, and increase aggregate stability (Mutchler and McDowell, 1990; Alliaume et al., 2014; Moore et al., 2014; Finney et al., 2017; Rorick and Kladivko, 2017). As a result, fall planted crops can reduce particulate bound P runoff and nitrate leaching (Martinez and Guiraud, 1990; Cook, 1992; Thom et al., 2018; Quinn and Steinke, 2019). Although wheat can provide many of these benefits which may not be accounted for when making cropping decisions, farmers will likely continue to plant less wheat, unless it can produce an ROI competitive with soybeans and corn. Recent studies have shown that wheat yields and economic returns can be improved through improved management or use of inputs such as: seeding rate, nitrogen (N) rate and timing, sulfur (S) fertilizer, and fungicides (Girma et al., 2005; Swoish and Steinke, 2017; Quinn and Steinke, 2019; Jaenisch et al., 2019; Lindsey et al., 2020).

Seeding rate is one of the easiest inputs for a farmer to control and plays a major role in determining final crop yield (Frederick and Marshall, 1985b; Joseph et al., 1985b). Optimum seeding rate is highly variable, depending on environmental conditions, seed quality, and management decisions (Roth et al., 1984; Marshall and Ohm, 1987; Geleta et al., 2002b). Traditionally, the recommended seeding rate for Ohio has been between 2.96–3.95 million seeds ha^{-1} when planting within 2 weeks of the Hessian fly (*Mayetiola destructor*)-free (Lindsey et al., 2017a). Recently, Lindsey et al. (2020) found that modern cultivars responded favorably to increased seeding rates with the agronomic optimum seeding rate being 3.46 to 4.76 million seeds ha^{-1}. They also found that the economic optimum seeding rate was slightly lower at 2.38 to 3.04 millions seeds ha^{-1} (Lindsey et al., 2020). Likewise, a study in Kansas found that in a no-till system, an increased seeding rate of 4 million seeds ha^{-1} improved grain yield by approximately 0.4 Mg ha^{-1} when compared to the traditional seeding rate of 2.78 million seeds ha^{-1} but did not improve economic returns (Jaenisch et al., 2019). These results suggest that wheat grain yield can be improved by increased seeding rate, but it may not be profitable so more research is needed to determine confirm prior results.

Nitrogen is another common input that farmers manage to influence grain yield. The current university recommended N rate is based on expected crop yield and ranges between 80 and 130 kg N ha^{-1} (Culman et al., 2020). Although it has recently been reported that some farmers in states surrounding Ohio are increasing N rates above the recommended rate to improve yields (Knott et al., 2016; Swoish and Steinke, 2017). Additionally, farmers may choose to adjust the timing of N application to increase crop yield. Previous research has shown that maximum crop N uptake occurs just before jointing (Feekes 5) and suggests that spring N be applied at or before this time (Weisz et al., 2001). This matches the current university recommendations of applying N between "green-up" (approximately Feekes 3-4) and "jointing" (Feekes 6) (Lindsey et al., 2017a). Although some farmers have suggested applying N early in the spring, prior to "green-up," to promote more tillering in the spring.

Since the adoption of strict pollution regulation by the United States in the 1990's, the atmospheric deposition of S has fallen significantly (US EPA, 2019). This reduction has led to an increased interest in S fertilizer to make up for S removed during crop harvest. Although recent research on S fertilization of wheat is lacking, one study in Kansas found that the addition of S fertilizer increased winter wheat grain yield by 0.3 Mg ha^{-1} across two years in a no-till location (Jaenisch et al., 2019). In Ohio, the use of S fertilizer has been shown to increase corn yield by an average of 0.53 Mg ha^{-1} and improve N uptake (Chen et al., 2008). Additionally, another study showed that alfalfa and soybean yields can be increased by the addition of S fertilizer (Chen et al., 2005). These results suggest that S fertility may be lacking in some Ohio soils and wheat farmers may benefit from the use of S fertilizer but more research is necessary.

Many producers in Ohio utilize a fungicide to control fungal diseases throughout the wheat growing season. Farmers commonly applied at Feekes 9 to protect the flag leaf and/or at Feekes 10.5.1 to protect against Fusarium head blight (Cook et al., 1999; Paul et al., 2018; Jaenisch et al., 2019). Previous research in Michigan, Kansas, and Wisconsin has shown that the inclusion of a foliar fungicide can protect wheat from disease and lead to higher yields but changes to economic returns are mixed with Quinn and Steinke, (2019) and Jaenisch et al. (2019) finding no increased return and Roth et al. (2020) finding increased profits. Application timing of the fungicide varied between vegetative growth (Feekes 6 or 9), reproductive growth (Feekes 10.5.1), and both depending on the study and treatment combination which may have resulted in the different yield and economic results.

Although these results show that additional inputs can individually improve the yield of wheat, little research has been done on the combined effect these inputs, and none in Ohio. The omission trial is an experimental design that has previously been used to evaluate intense management of many different crops and elucidate the affects of removing or adding specific inputs from a intense or traditional management system respectively (Bluck et al., 2015; Ruffo et al., 2015; Quinn and Steinke, 2019; Jaenisch et al., 2019). Quinn and Steinke (2019) and Jaenisch et al. (2019) used an omission trial in Michigan and Kansas, respectively, to identify inputs that could be used to improve grain yield and economic returns, but their results may not be applicable to Ohio because of the different environment and class of wheat grown. Therefore, the objective of this study was to identify if seeding rate, increased N, split N applications, S fertilizer, and fungicides can be used individually or in combination to increase grain and straw yield, improve grain quality, and increase economic returns of soft red winter wheat grown in Ohio.

2.3. Materials and Methods

2.3.1. Site Description and Experimental Design

This study was established at two locations in Ohio over the 2019-2020 and 2020-2021 growing seasons, for a total of four site-years. The study was performed at the Western Agricultural Research Station (WARS) in Clark County (39° 51' 45.21" N, 83° 40' 20.66" W) and at the Northwest Research Station (NWARS) in Wood County (41° 11' 49.29" N, 83° 45' 53.71" W). At WARS, the soil was a Strawn-Crosby complex (fine-loamy, mixed, mesic Typic Hapludalfs) and Kokomo silty clay loam (fine, mixed, superactive, mesic Typic Argiaquolls) and at NWARS the soil was Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualfs). The plots were eight 19 cm rows wide and measured 1.5 m by 7.62 meters. The study was a randomized complete block, incomplete factorial omission trial with four replications (Florence, 2012; Henninger, 2012). Seven agronomic inputs and management techniques were evaluated: seeding rate, N fertilizer rate, N fertilizer application timing, S fertilizer, and two foliar fungicide application timings (Table 1). The traditional management (TM) consisted of common practices in Ohio with the university-recommended seeding rate, one spring N fertilizer application, a yield-based N application rate, no S fertilizer, and no foliar fungicide. The intensive management (IM) increased the seeding rate and N rate compared to the TM, split the N into two spring applications, added S fertilizer, a fungicide application at Feekes 9, and a fungicide application at Feekes 10.5.1.

Table 1. Overview of omission treatment design, treatment names, and inputs.

Treatment	Treatment Name	Inputs					
		High SR†	High N‡	Split N§	S¶	Fungicide 9#	Fungicide 10.5.1††
1	Intensive management (IM)	Yes	Yes	Yes	Yes	Yes	Yes
2	IM – high SR	No	Yes	Yes	Yes	Yes	Yes
3	IM – high N	Yes	No	Yes	Yes	Yes	Yes
4	IM – split-N	Yes	Yes	No	Yes	Yes	Yes
5	IM – S	Yes	Yes	Yes	No	Yes	Yes
6	IM – fungicide 9	Yes	Yes	Yes	Yes	No	Yes
7	IM – fungicide 10.5.1	Yes	Yes	Yes	Yes	Yes	No
8	Traditional management (TM)	No	No	No	No	No	No
9	TM + high SR	Yes	No	No	No	No	No
10	TM + high N	No	Yes	No	No	No	No
11	TM + split-N	No	No	Yes	No	No	No
12	TM + S	No	No	No	Yes	No	No
13	TM + fungicide 9	No	No	No	No	Yes	No
14	TM + fungicide 10.5.1	No	No	No	No	No	Yes

† High seeding rate of 4.94 million seeds ha^{-1}
‡ High N rate consisted of 120% of recommended rate in the Tri-State Fertilizer Guide
§ Split N consisted of 25% of N applied at Feekes 3-4 and the remainder at Feekes 5-6
¶ S fertilizer (gypsum) applied at 17.9 kg S ha^{-1} at Feekes 5-6
# Foliar fungicide applied at a rate of 584 mL ha^{-1} at Feekes 9
†† Foliar fungicide applied at a rate of 292 mL ha^{-1} at Feekes 10.5.1

2.3.2. Cultural Practices and Treatments

At all locations, the previous crop was soybean, and the plots were tilled prior to planting using a field cultivator at WARS and a disc followed by a field cultivator at NWARS. Just prior to planting, eight to ten soil samples were collected to a 20 cm depth and aggregated for the whole field each year at both locations and analyzed for soil chemical and physical properties (Supplemental Table 1). Monthly average temperature and cumulative precipitation were collected from the on-site CFAES weather stations. Each year, the plots were planted after the Hessian fly (*Mayetiola destructor*) safe date for each location (Table 2). Both years the wheat was planted using a custom-built planter with Great Plains 20 series row units, a Singulator-Plus seed meter, and high-rate wheat seed disk (Great Plains Ag, Salina, KS) and the cultivar used was AGI 217B (Advanced Genetics Inc., Croton, OH). The traditional seeding rate was 2.96 million seeds ha^{-1}, and the high seeding rate was 4.94 million seeds ha^{-1}.

Table 2. Dates of field operations and treatment applications.

	2019-2020 Growing Season		2020-2021 Growing Season	
	WARS †	NWARS ‡	WARS	NWARS
Planting	1 October 2019	14 October 2019	9 October 2020	25 November 2020
Early Nitrogen	12 March 2020	9 March 2020	20 March 2021	21 March 2021
Nitrogen	19 March 2020	19 March 2020	6 April 2021	11 April 2021
Sulfur	19 March 2020	19 March 2020	6 April 2021	11 April 2021
First fungicide	11 May 2020	23 May 2020	6 May 2021	13 May 2021
Second fungicide	21 and 24 May 2020	30 May 2020	27 May 2021	27 May 2021
Straw Harvest	9 July 2020	8 July 2020	29 June 2021	30 June 2021
Grain Harvest	9 July 2020	8 July 2020	7 July 2021	5 July 2021

† Western Agricultural Research Station
‡ Northwest Agricultural Research Station

In the spring, an early application of 20% of the total N fertilizer (urea) was hand broadcast at Feekes growth stage 4 (Table 2) on the IM and the TM + spilt N plots. The remaining N and S (gypsum) fertilizer were applied at Feekes growth stage 5 using the same method (Table 2). Any weeds present were controlled at this time using appropriately labeled herbicides. The flag leaf fungicide treatment was applied in the late spring (Table 2) around the Feekes 9 growth stage using a backpack sprayer calibrated for 140 L ha^{-1} and a 1.5 m hand boom with Teejet flat fan nozzles (TT110015) and consisted of a Propi-Star EC (Propiconazol {1-(2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-ylmethyl)-1h-1,2,4-triazol}; Albaugh, LLC, Ankeny, IA) at 584 mL ha^{-1}. At the beginning of anthesis (Feekes 10.5.1)(Table 2) a second fungicide treatment of Prosaro 421 SC (prothioconazole {2-[2-(1-chlorocyclopropyl0–3-(2-chlorophenyl)-2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione} and tebuconazole {α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol}; Bayer CropScience Research Triangle Park, NC) was applied at 292 mL ha^{-1}. A non-ionic surfactant (X99 Super Surfactant, Alkyl and Alkylaryl Polyoxethylene Glycol; Heartland Ag, Inc., Farmer City, IL) was used with each fungicide application at 35 mL ha^{-1}.

At maturity (Feekes 11.4), the grain was harvested (Table 2) using a small plot combine (Wintersteiger Quantum, Salt Lake City, UT) equipped with a Harvest Master Classic GrainGage (Juniper Systems, Logan, UT). An approximately 0.5 kg grain sample was collected from each plot and after harvest the grain sample was cleaned using a belt thresher (BT14, Almaco, Nevada, IA) and analyzed for the mycotoxin, deoxynivalenol (DON) using a Reveal Q+ for DON quick strip test kit (Neogen, Lansing, MI) using the methods outlined by the manufacturer and van der Fels-Klerx and de Rijk (2014).

2.3.3. In-Season Measurements

In the fall (Table 3), at approximately Feekes growth stage 1, a stand assessment was made at each location. At three random points in the plot the number of plants in a 30.5 cm section of row was recorded and averaged for a whole plot value. In the spring of 2021 (Table 3) at approximately Feekes growth stage 5, the same protocol was used to quantify the number of stems. Spring stem counts did not happen during 2020 due to the Covid-19 pandemic that prevented travel to the research locations.

At approximately Feekes 9 growth stage, the fungicide treatment was applied and approximately two weeks later (Table 3) the flag leaf was evaluated for disease severity and incidence using methods found in Roth et al. (2020). At five points arbitrarily selected within the plot a sample of 20 flag leaves was visually estimated for disease severity (percent of leaf area affected by disease utilizing a standard area diagram (Nutter Jr. and Litwiller, 1998) and incidence (number of diseased leaves). These five ratings were averaged for a whole plot disease severity and incidence rating, the specific disease was not reported. At the time of the first fungicide application (Table 2), and at each subsequent trip to the plots (Table 2 and Table 3), the percentage of each plot that was lodged was estimated. At approximately Feekes 10.5 (Table 3), a plant tissue sample of 50 flag leaves were collected from each plot and analyzed for nutrient content at a commercial testing laboratory (A&L Great Lakes, Fort Wayne, Indiana). During or shortly after anthesis (Feekes 10.5.1) a second fungicide treatment was applied and approximately 2 weeks later (Table 3) the spikes were rated for conditional severity and incidence of Fusarium head blight using the methods described by Salgado et al. (2017) and Paul et al. (2005). At five arbitrarily selected points within each plot a sample of 20 spikes was visually estimated for the number of diseased spikes and the percentage of diseased spikelets on infected spikes. These five measurements were averaged to estimate the disease severity and incidence for the whole plot.

Table 3. Dates of Field Measurements

	2019-2020 Growing Season		2020-2021 Growing Season	
	WARS Date†	NWARS Date‡	WARS Date	NWARS Date
Fall Stand Count	25 October 2019	22 November 2019	21 December 2020	22 December 2020
Spring Stem Count	N/A§	N/A	6 April 2021	7 April 2021
Flag Leaf Disease Rating	11 May 2020	25 May 2020	6 May 2021	20 May 2021
Flag Leaf Tissue Sample	28 May 2020	1 June 2020	4 June 2021	27 May 2021
Fusarium Head Blight Disease Rating	12 June 2020	15 June 2020	15 June 2021	14 June 2021

† Western Agricultural Research Station
‡ Northwest Agricultural Research Station
§ During the 2019/20 growing season spring stem counts were not completed due to the Covid-19 pandemic preventing travel to the research stations

Prior to grain harvest (Table 2), a straw sample was collected from a 30 cm length of row in 2 adjacent rows. The wheat was clipped approximately 10-15 cm above the ground and the heads were removed, to approximate the straw that would be left after combine harvesting. The samples were then dried at 60° C in a forced air dryer for two days before being weighed to estimate straw yield. During harvest (Table 2) the grain mass, moisture, and test weight was recorded by the plot combine and used to calculate grain yield adjusted to 135 g kg^{-1} moisture content.

2.3.4. Economic analysis

A typical dockage schedule was developed by taking the median values from a number of local grain elevators and end-users and can be found by following this link to Supplemental File 1. This dockage schedule was used to estimate price deduction for each treatment based on moisture, test weight, and DON concentration. Gross income was calculated by multiplying average grain yield minus any shrink by \$187.39 ton^{-1} (\$5.10 bu^{-1}) minus any price deductions and the average straw yield by \$108.86 Mg^{-1} (\$120 US ton^{-1}). Prices for grain, straw, N, and seed were taken from the 2020 Ohio State Extension Wheat Production Budget (Ward et al., 2020). Only the expenses that changed with the treatments were accounted for in this analysis. The expenses were \$0.031 per 1000 seeds, \$944.84 Mg N^{-1}, \$1,687.91 Mg S^{-1}, \$23.12 L^{-1} of Feekes 9 fungicide, \$79.52 L^{-1} of Feekes 10.5.1 fungicide, \$18.53 ha^{-1} of liquid product application (N and fungicides), \$17.30 ha^{-1} of dry product application (S). Sulfur and fungicide prices were averaged from three different Ohio agricultural retailers. Applications costs came from the 2020 Ohio State Extension Custom Farm Rates Survey (Ward, 2020). Individual treatment costs were calculated by summing the cost for each input applied and varied by location due different N rates but were consistent across years (Supplemental File 1). Treatment costs were then subtracted from the gross income to calculate the partial returns.

2.3.5. Statistical Analysis

Each site-year was analyzed separately due to treatment by location and treatment by year interactions. Data were analyzed using the PROC GLIMMIX procedure in SAS 9.4 at α = .05 with treatment as the fixed effect and replication as the random effect (SAS Institute, Cary, NC). Flag leaf disease and FHB incidence were transformed using an arcsine-square root transformation for all site-years. A square root transformation was used for flag leaf conditional severity at WARS in 2021 and NWARS both years and a square transformation was used at WARS in 2020. For FHB conditional severity at both locations, in 2020, a square transformation was used and in 2021, a square root transformation was used. At WARS a square root transformation was needed for the DON concentration data for both years. For all transformations, back transformed means are presented. Mean separations were determined using single degree of freedom contrasts. The preplanned comparisons consist of the IM to the TM, omitted treatments to the IM, and added treatments to the TM (Florence, 2012; Henninger, 2012).

2.4. Results and Discussion

2.4.1. Overview

On average, grain and straw yields were 30% and 14% higher, respectively, in the 2020-2021 growing season than in the 2019-2020 growing season (Table 4 and Table 5). This is likely due to increased precipitation during the early summer and cooler temperatures in July 2021 during grain filling (Table 6). Additionally, on average, NWARS produced a 11% higher grain yield but a 18% lower straw yield than WARS (Table 4 and Table 5). This is likely due to being located at a higher latitude and having shorter growing season to produce above ground biomass. Although, this location normally has cooler temperatures during the mid-summer allowing for a longer grain filling period and higher grain yields (Table 6).

Table 4. Average grain yield by site-year. Average yield shown for IM and TM and change in yield from IM or TM shown for all other treatments, respectively.

	2020		2021	
Treatment	WARS†	NWARS‡	WARS	NWARS
	--------------------------Mg ha^{-1}	------------------------------		
Intensive Management (IM)	4.94	6.35	7.62	7.31
IM - High SR§	-0.08	-0.08	+0.01	-0.2
IM - High N	-0.18	-0.76	-0.10	-0.24
IM - Split N	-0.01	-0.23	-0.28	-0.44*
IM - S	-0.08	+0.18	-0.27	+0.04
IM - Fungicide 9	-0.72*	-0.21	-0.03	-0.11
IM – Fungicide 10.5.1	-0.47	-0.53	-0.63*	-0.08
Traditional Management (TM)	4.30	6.56	6.62	6.46
TM + High SR#	-0.50	-0.41	+0.06	+0.13
TM + High N	+0.45	-0.73	+0.05	+0.13
TM + Split N	-0.19	-0.43	+0.20	+0.29
TM + S	-0.31	-0.23	+0.03	-0.004
TM + Fungicide 9	+0.81*	-0.03	+0.23	+0.21
TM + Fungicide 10.5.1	+0.79**	-1.05	+0.52*	+0.25
IM vs TM	+0.65*	-0.21	+1.00***	+0.85***

* Significantly different at $\alpha \leq .05$ using single degree of freedom contrasts.
** Significantly different at $\alpha \leq .01$ using single degree of freedom contrasts.
*** Significantly different at $\alpha \leq .001$ using single degree of freedom contrasts.
† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
§ Yield values of IM minus input are reported as change in yield from IM treatment.
# Yield values of TM plus input are reported as change in yield from TM treatment.

Table 5. Average straw yield by site-year. Average yield shown for IM and TM and change in yield from IM or TM shown for all other treatments respectively.

	2020		2021	
Treatment	WARS†	NWARS‡	WARS	NWARS
	--------------------------Mg ha^{-1}	------------------------------		
Intensive Management (IM)	7.87	7.17	9.57	8.61
IM - High SR§	+0.20	+0.34	+0.52	-0.13
IM - High N	+0.15	-0.90	+0.22	+0.30
IM - Split N	+0.68	-0.51	+0.78	-0.67
IM - S	+0.11	+0.19	+1.37	-0.81
IM - Fungicide 9	+2.17	-0.9	-0.06	+0.27
IM - Fungicide10.5.1	+1.57	-0.25	+1.21	+0.86
Traditional Management (TM)	8.55	7.75	8.36	7.78
TM + High SR#	+1.42	-0.55	+0.24	+0.19
TM + High N	+0.05	-1.60*	-1.00	+0.54
TM + Split N	+0.64	-1.04	+2.21*	+0.86
TM + S	+1.08	-0.46	+0.18	+0.81
TM + Fungicide 9	-0.79	-0.58	+0.27	+0.08
TM + Fungicide 10.5.1	-0.75	-1.33	+0.29	+0.70
IM vs TM	-0.68	-0.58	+1.22	+0.83

* Significantly different at $\alpha \leq .05$ using single degree of freedom contrasts.
† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
§ Yield values of IM minus input are reported as change in yield from IM treatment.
# Yield values of TM plus input are reported as change in yield from TM treatment.

Table 6. Average monthly air temperature and total precipitation for the 2019-2020 and 2020-2021 growing seasons and 30-yr period (1991-2020) at WARS and (NWARS). Data shown as difference from 30 year normal.

	WARS†				NWARS‡			
	30-yr	2019	2020	2021	30-yr	2019	2020	2021
	----------------			°C			----------------	
January	-2.3		+4.1	+1.8	-3.2		+4.0	+3.0*
February	-0.5		+5.5	-3.3	-1.7		+0.9	-3.0*
March	4.5		+3.4	+2.8	3.3		+2.3	-4.9*
April	11.0		-1.6	+0.1	9.7		-1.5	+1.1
May	17.0		-1.8	-1.3	16.2		-1.3	-0.5
June	21.6		+0.7	+0.9	21.4		+1.3	+1.4
July	23.1		+1.8	-0.2	23.1		+1.9	-0.4
August	22.1		-0.1	+1.4	21.8		+0.3	+1.4
September	18.4	+3.2	-0.3		18.1	+2.5	-0.3	
October	12.1	+1.7	-0.4		11.8	+0.8	-0.4	
November	5.5	-2.9	+2.4		5.1	-2.7	+2.6	
December	0.3	+2.1	+0.5		-0.3	+2.1	+1.7*	
	----------------			cm			----------------	
January	61.3		-6.4	-57.0	46.1		+34.5	-16.1*
February	48.6		-48.6	-29.8	44.7		-7.1	-29.9*
March	75.7		+6.8	-29.2	53.1		+31.8	+3.6*
April	93.0		+14.7	-33.0	79.6		-42.3	-18.9
May	102.3		+13.8	-31.4	96.3		+21.1	-15.7
June	97.0		-63.2	-18.8	85.1		-52.6	+7.4
July	113.7		-44.4	+27.7	95.6		-46.9	+12.3
August	67.7		+1.9	+19.1	86.0	+37.2	-20.5	-3.2
September	76.8	-49.9	-32.3		66.6	+21.6	-18.4	
October	71.5	-11.5	26.1		69.1	-46.4	+35.3	
November	66.7	-36.2	-22.3		60.8	-6.5	+3.4	
December	71.7	-24.9	-51.1		51.0	+37.2	-33.5*	

† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
* Data collected from the Findlay, OH airport (NOAA) due to the on-farm weather station undergoing maintenance.

2.4.2. Grain Yield

2.4.2.1. Intense Management vs Traditional Management

At three of the four site years in this study, the IM increased grain yield when compared to the TM (Table 4). At WARS, the IM significantly increased grain yield by 0.65 Mg ha^{-1} and 1.00 Mg ha^{-1} in 2020 and 2021, respectively. At NWARS, grain yield was only improved in 2021 and was significantly increased by 0.85 Mg ha^{-1} compared to the TM. This suggests that in some years the TM system can benefit from the addition of one or more inputs.

2.4.2.2. Seeding Rate

The removal of the high seeding rate from the IM and the addition of the high seeding rate to the TM did not significantly change grain yield at any site-year in this study (Table 4). This likely due to the traditional seeding rate (2.96 million seeds ha^{-1}) being within the university recommended range when planted within two weeks of the hessian fly-free date as outlined by Lindsey et al. (2017). At three of the site-years wheat was planted within two weeks of the fly-free date but at NWARS in 2020, planting was delayed 21 days (Table 2) although no yield benefit was seen from the increased seeding rate. In addition, Lindsey et al. (2020) found that in Ohio the economic optimum seeding rate was 2.55 to 3.04 million seeds ha^{-1} using a linear plateau model and the agronomic optimum was slightly higher at 2.85 to 3.48 million seeds ha^{-1} with seeding rates above these ranges providing little or no economic or yield benefits.These results suggest that the lack of yield response found in this study is due to the traditional seeding rate already being optimized for the growing conditions in Ohio and the high seeding rate providing no additional benefit when wheat is planted timely.

2.4.2.3. Nitrogen Rate

Increasing the N rate in the TM and removing the additional N from the IM did not significantly change grain yield at any site-year (Table 4). Lack of yield response may be the result of adequate N fertilization at the traditional rate due to this rate being the current university recommended (Culman et al., 2020). Additionally, the four site-years in this study generally did not have environmental conditions that favored N loss such as intense rainfalls and extended periods of water-logged soils (Bock, 1984; Reddy et al., 1984; Fageria, 2009; Liu et al., 2014). During this study the precipitation for March and April, the time of maximum crop N uptake (Weisz et al., 2001; Lindsey et al., 2017b), was 4% above and 26% below the 30 year normal in 2020 and 2021, respectively (Table 6) resulting in the extra N not being necessary to account for N lost through leaching and denitrification. These results align with those found by researchers in Kentucky, Michigan, and Kansas who found that additional N above the locally-recommended rate did not produce a consistent yield increase (Knott et al., 2016; Swoish and Steinke, 2017; Quinn and Steinke, 2019; Jaenisch et al., 2019). The authors attributed their results to dry spring conditions reducing environmental N loss and plant N uptake (Swoish and Steinke, 2017) as well as the sufficiency of local N recommendations (Knott et al., 2016; Quinn and Steinke, 2019).

2.4.2.4. Split Nitrogen Application

In 2021 at NWARS, the removal of the split N treatment from the IM significantly decreased yield by 0.44 Mg ha^{-1} (Table 4). All other site-years did not show a yield response to the split N application. These results align with those found by Roth and Marshall (1987) who concluded that split and delayed N applications after Feekes 3 did not increase yield unless N was lost due to leaching and denitrification. Likewise, Gravelle et al. (1988) determined a split application of N at tillering (Feekes 3-5) and at heading (Feekes 10) only increased grain yield and improved N use efficiency on the sandy loam soils of the Virginia coastal plain due to the increased risk of N loss. Therefore, limited yield response of this study may be attributed to a lack of conditions favoring N loss such as intense rainfalls and extended periods of water-logged soils during the two years of this study (Table 1) (Bock, 1984; Reddy et al., 1984; Fageria, 2009; Liu et al., 2014). During this study, the precipitation for the major portion of the growing season (March to June) (Lindsey et al., 2017b) was 10% and 20% below the 30 year normal in 2020 and 2021 respectively (Table 1) resulting in the split N application not being necessary to account for N lost through leaching and denitrification.

2.4.2.5. Sulfur Fertilizer

The removal of S from the IM and the addition of S to the TM did not significantly change the grain yield at any of the site-years (Table 4). At the heading growth stage (Feekes 10.5) and later, flag leaf S content between 0.1 to 0.3% is considered adequate to maintain crop yield ("Fact Sheet No. 35," 2009; Dick et al., 2015). All the flag leaf samples collected were within or above this range (Supplemental Table 2) and no visual S deficiency symptoms were observed, suggesting that S fertilization was adequate regardless S treatment. These results align with Lentz and Mullen (2006) who found that, in Ohio, wheat grain yield was not significantly effected by S fertilizer. Likewise, Thomason et al. (2007) who found that the application of 34 kg ha^{-1} of S did not significantly change the grain yield of hard red winter wheat but it did increase grain protein concentration at two of the three locations in Virginia, USA. They attributed this difference by location to different mineral holding capacities of the soils (Thomason et al., 2007). On the other hand, Wilson et al. (2020) found that wheat yield was significantly increased both years of their study by the application of a S fertilizer which they attributed to the coarse textured, low organic matter soils where they conducted the study. The results of these studies suggest that the grain yield response of wheat to S fertilizer is likely dependent on soil type and the soils (Supplemental Table 1) in this study supplied adequate S resulting in no response to additional S.

2.4.2.6. Feekes 9 Foliar Fungicide

At WARS in 2020, the addition of a foliar fungicide at Feekes 9 to the TM significantly increased yield by 0.81 Mg ha^{-1} and the removal of the fungicide from the IM significantly reduced yield by 0.72 Mg ha^{-1} (Table 4). The yield effect at WARS in 2020 is likely the result of increased mid-season foliar disease severity on the flag leaf because, across all treatments, the average flag leaf foliar disease conditional severity was higher in 2020 than it was in 2021 at that location (Supplemental Table 3). Many fungal pathogens of wheat are favored by cool, humid weather thus the higher disease incidence and severity may be the result of increased rainfall and cooler temperatures during April and May that year compared to the 2020-2021 growing season and the 30-yr normal (Table 6) (Salgado et al., 2016). Overall, these results show that a foliar fungicide applied at the Feekes 9 timing is likely to only be beneficial if conditions are favorable for foliar disease and the critical thresholds found in the Ohio Agronomy Guide are exceeded. These thresholds are 1% of leaf area affected on the leaf below the flag leaf before Feekes 10 or 1% of the flag leaf affected between Feekes 10 and 10.5 (Lindsey et al., 2017a).

2.4.2.7. Feekes 10.5.1 Foliar Fungicide

Application of a foliar fungicide at Feekes 10.5.1 produced significant grain yield effects at WARS during the two years of this study (Table 4). The addition of the fungicide to the TM increased yield by 0.79 Mg ha^{-1} and 0.52 Mg ha^{-1} in 2020 and 2021, respectively, at WARS. The removal of the fungicide from the IM did not significantly change yield in 2020 but did significantly decreased yield by 0.63 Mg ha^{-1} in 2021 at WARS. Although there were significant yield effects from the addition or removal of a foliar fungicide there was not a significant difference in FHB incidence or conditional severity at either site year (Supplemental Table 3 and Supplemental Table 4). This may be a due to the overall low levels of FHB during the two years of this study. The yield effect from the foliar fungicide application may be the result of increased green leaf area from reduced foliar disease (which was not measured at anthesis) during grain fill as well as delayed leaf senescence as described by Cook et al. (1999) and Bertelsen et al. (2001).

2.4.3. Straw Yield

Straw yields ranged from 6.15 to 10.94 Mg ha^{-1} with an average yield of 8.35 Mg ha^{-1} across all site-years (Table 5). Yields were generally higher at WARS than NWARS which may be due to more growth in the fall (Supplemental Table 5) and warmer spring temperatures (Table 6) resulting more aboveground biomass growth. Across all comparisons, only two inputs resulted in a significant difference. At NWARS in 2020, the addition of the high N treatment to the TM resulted in an average decrease of 1.6 Mg ha^{-1} (Table 5) and at WARS in 2021, the addition of the split N treatment to the TM resulted in a yield increase of 2.21 Mg ha^{-1} (Table 5). The general lack of consistent response on straw yield from the addition or removal of treatments shows that for the cultivar we tested, aboveground biomass production is likely more dependent on the environment than management. This is similar to the results found by Dai et al. (2016), who concluded that variations precipitations was likely the most influential factor effecting straw yields across the cultivars and cultural practices used in their study.

2.4.4. Deoxynivalenol Content

In general, all site-years had low levels of DON contamination and were below 2 mg kg^{-1} dockage thresholds used by most local grain elevators and end-users (Supplemental File 1). Additionally, NWARS had lower levels of disease and DON concentration in the harvested grain (Table 7), resulting in the DON content at NWARS being insignificant in both years, so only results from WARS are discussed.

Table 7. Average deoxynivalenol (DON) concentration by site-year. Average concentration shown for IM and TM and change in concentration from IM or TM shown for all other treatments respectively.

Treatment	2020		2021	
	WARS†	NWARS‡	WARS	NWARS
	--------------------------mg kg^{-1}		------------------------------	
Intensive Management (IM)	0.22	0.20	0.28	0.12
IM - High SR§	-0.00	-0.02	-0.12	-0.07
IM - High N	+0.03	-0.03	-0.01	-0.06
IM - Split N	-0.01	-0.04	+0.18	-0.08
IM - S	+0.00	-0.01	-0.14	-0.04
IM - Fungicide 9	-0.05	-0.03	-0.13	+0.00
IM - Fungicide10.5.1	+0.41**	-0.02	+0.69**	+0.08
Traditional Management (TM)	1.23	0.20	1.10	0.11
TM + High SR#	-0.40	-0.00	+0.02	+0.15
TM + High N	-0.23	-0.02	-0.07	+0.15
TM + Split N	+0.03	-0.02	-0.08	+0.10
TM + S	-0.05	-0.02	+0.38	+0.08
TM + Fungicide 9	-0.44*	-0.05	-0.11	+0.09
TM + Fungicide 10.5.1	-1.05***	-0.02	-0.81***	-0.01
IM vs TM	-1.01***	-0.00	-0.82***	+0.01

* Significantly different at $\alpha \leq .05$ using single degree of freedom contrasts.
** Significantly different at $\alpha \leq .01$ using single degree of freedom contrasts.
*** Significantly different at $\alpha \leq .001$ using single degree of freedom contrasts.
† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
§ DON values of IM minus input are reported as change in yield from IM treatment.
# DON values of TM plus input are reported as change in yield from TM treatment.

Intense management significantly reduced DON content by 1.00 mg kg^{-1} in the 2019-2020 growing season and 0.82 mg kg^{-1} in the 2020-2021 growing season (Table 7). This is likely due to the inclusion of a fungicide in the IM because the addition or removal of a fungicide were the only contrasts that produced significantly different results. The removal of the Feekes 10.5.1 fungicide from the IM significantly increased DON content by 0.41 and 0.69 mg kg^{-1} in 2020 and 2021, respectively (Table 7). Likewise, in 2020 the addition of a fungicide at Feekes 9 or Feekes 10.5.1 to the TM reduced DON content by 0.44 and 1.05 mg kg^{-1} and in 2021 the addition of a fungicide at Feekes 10.5.1 reduced DON content by 0.81 mg kg^{-1} (Table 7). Although DON content was reduced, there was not a significant reduction in visible FHB index (data not shown) as defined by Paul et al. (2005) and Stack and McMullen (2011). The reduction in DON content without a reduction in FHB matches the findings of Yoshida et al. (2011), who found that the application of a fungicide up to 20 days after anthesis reduces DON concentration but may not reduce FHB incidence or severity.

2.4.5. Partial Returns

In general, the 2020-2021 growing season resulted in higher partial returns across locations. This was a result of the higher grain and straw yields during that growing season (Table 4 and Table 5). Across all four site-years of this study the IM never significantly increased partial returns above the TM (Table 8). Although, in 2020 at NWARS the addition of a fungicide at Feekes 10.5.1 to the TM significantly decreased returns by \$410.05 ha^{-1} (Table 8). This is likely due to the increased cost of applying the fungicide and an insignificant change in yield resulting in a lower return (Table 4). On the other hand, at WARS in 2021 the addition of split N to the TM significantly increased returns by \$321.01 ha^{-1} (Table 8). This increase in returns is due to a significantly higher straw yield from that treatment at that site-year; increasing the total income and offsetting the additional cost of split applying N (Table 5).

Table 8. Average partial returns by site-year. Average partial returns shown for IM and TM and change in returns from IM or TM shown for all other treatments respectively.

	2020		2021	
Treatment	WARS†	NWARS‡	WARS	NWARS
	------------------------USD ha^{-1}------------------------			
Intensive Management (IM)	$ 1,451.84	$ 1,701.04	$ 2,235.67	$ 2,068.46
IM - High SR§	$ 80.70	$ 88.67	$ 131.76	$ 4.35
IM - High N	-$ 30.26	-$ 242.91	$ 31.96	$ 15.15
IM - Split N	$ 150.70	-$ 99.95	$ 61.92	-$ 151.51
IM - S	$ 150.70	$ 107.25	$ 184.18	-$ 47.34
IM - Fungicide 9	$ 146.65	-$ 128.35	$ 16.70	$ 44.95
IM - Fungicide10.5.1	$ 135.67	-$ 128.35	$ 62.65	$ 141.61
Traditional Management (TM)	$ 1,595.07	$ 2,032.44	$ 2,078.80	$ 2,015.34
TM + High SR#	$ 22.01	-$ 208.55	-$ 18.50	-$ 8.15
TM + High N	$ 97.09	-$ 366.93	-$ 137.16	$ 74.92
TM + Split N	$ 28.90	-$ 232.25	$ 321.01*	$ 151.90
TM + S	$ 46.29	-$ 157.21	-$ 21.08	$ 37.75
TM + Fungicide 9	$ 83.53	-$ 109.31	$ 43.18	$ 22.55
TM + Fungicide 10.5.1	$ 93.38	-$ 410.05*	$ 125.94	$ 102.58
IM vs TM	-$ 143.23	-$ 331.40	$ 156.88	$ 53.12

* Significantly different at $\alpha \leq .05$ using single degree of freedom contrasts.
† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
§ Partial returns of IM minus input are reported as change in yield from IM treatment.
# Partial returns of TM plus input are reported as change in yield from TM treatment.

These results were inconsistent across the four site-years of the study suggesting that, in most cases the additional inputs and the complete IM system do not justify the costs and lead to higher returns. This result is consistent with the finding of Quinn and Steinke (2019) and Jaenisch et al. (2019) who found that in Michigan and Kansas, respectively, IM has the potential to increase grain yields but failed to increase economic returns. They attributed the lack of increased economic returns to a lack of yield limiting conditions (Quinn and Steinke, 2019) and low wheat prices (Jaenisch et al., 2019) during the years of the studies. Although these studies and the results of this study conflict with Roth et al. (2020) who found that in Wisconsin, both mid-level and intense management increased grain yields and economic returns above the TM with the mid-level returning the most. They attributed their results to increased grain and straw yield as well as a decrease DON concentration from the mid-level and intense management (Roth et al., 2020).

2.5. Conclusion

The results of this study suggest that IM has the potential to increase wheat grain yield and quality but does not do so economically. Intensive management significantly increased grain yield at three of the four site-years in this study with the significance of individual inputs varying by location and year. Inconsistent or insignificant results were observed for seeding rate, high N, split N, S fertilization, and Feekes 9 fungicide on grain yield, straw yield, and DON concentration across all four site-years. Although, at WARS, the use of a fungicide at Feekes 10.5.1 did consistently increase grain yield and decrease DON concentration. But the improvements in grain yield and quality were not enough offset the cost of application at the prices used in this study. The use of a foliar fungicide at Feekes 10.5.1 did not significantly change yield at NWARS either year, suggesting that this response is location dependent.

Although IM improved grain yield and quality above the TM it did not significantly change partial returns. Additionally, the application or removal of an individual input from the TM or IM respectively did not consistently result in a significant change in partial returns. This suggests that during this study there was no difference between the economic returns of the IM and TM. Therefore, our recommendations to farmers are to continue to use the traditional, university recommended seeding and fertilizer recommendations and use crop scouting and disease outbreak modelling tools such as www.wheatscab.psu.edu to evaluate changing field conditions to determine if a fungicide application is necessary.

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Chapter 3: Economic Return Calculator to Estimate the Value of Inputs for Wheat Production

3.1. Introduction

In Ohio, wheat is the third most commonly planted row crop by area but the long term trend from 2000 to 2020 has been an approximately 50% decrease in Ohio wheat acreage (USDA NASS, 2020b). This is likely due to consistently low returns on investment (ROI), especially when compared to soybean and corn (Gillespie, 2019). As such, farmers in Ohio typically regard wheat as a "low input" crop and expect low yields and low returns. However, some farmers take a different approach and intensively manage wheat with many inputs and expect high yields and returns.

Additionally, wheat can provide both the farmer and the surrounding environment with benefits that are not always accounted for when making cropping decisions. Primarily, wheat diversifies farmers income by selling both the grain and the straw as well as providing the opportunity to double or intercrop with soybeans, further increasing the potential to make money. Also, research has shown that including wheat in a crop rotation can increase the yield of the subsequent soybean crop by as much as 5% (Huo et al., in press) and winter crops, such as wheat, can improve soil biological activity, reduce soil erosion, and increase aggregate stability (Finney et al., 2017; Rorick and Kladivko, 2017). As a result, fall planted crops can reduce particulate bound P runoff and nitrate leaching (Martinez and Guiraud, 1990; Thom et al., 2018). Although these benefits are often not accounted for when making cropping decisions; as such farmers will likely continue to plant less wheat, unless it can produce an ROI competitive with soybeans and corn. Recent studies have shown that wheat yields and economic returns can be improved through improved management or use of inputs such as: seeding rate, nitrogen (N) rate and timing, sulfur (S) fertilizer, and fungicides (Girma et al., 2005; Swoish and Steinke, 2017; Quinn and Steinke, 2019; Jaenisch et al., 2019; Lindsey et al., 2020). Therefore, the objective of this study was to develop a spreadsheet based tool to help farmers estimate the return on investment from several inputs commonly used in wheat production.

3.2. Methods

An omission trial was established at the Western Agricultural Research Station (WARS) near South Charleston, OH and the Northwest Agricultural Research Station (NWARS) near Custar, OH for two years (2019-20 and 2020-21). Each trial was replicated four times at each location. Seven agronomic inputs and management techniques were evaluated: seeding rate, N fertilizer rate, N fertilizer application timing, S fertilizer, and two foliar fungicide application timings (Table 9). Traditional management (TM) represented practices common in Ohio and followed university recommendations for wheat production. Intensive management (IM) increased the seeding and N rate, split the N into two spring applications, added S fertilizer, a generic fungicide application at Feekes 9, and a name-brand fungicide application at Feekes 10.5.1. Treatments were also individually applied to the TM or removed from the IM to allow for estimation of individual input affects. More information on specific treatments can be found below in Table 9 as well as in Chapter 2.

Table 9. Overview of omission treatment design, treatment names, and inputs.

Treatment	Treatment Name	Inputs					
		High SR†	High N‡	Split N§	S¶	Fungicide 9#	Fungicide 10.5.1††
1	Intensive management (IM)	Yes	Yes	Yes	Yes	Yes	Yes
2	IM – high SR	No	Yes	Yes	Yes	Yes	Yes
3	IM – high N	Yes	No	Yes	Yes	Yes	Yes
4	IM – split-N	Yes	Yes	No	Yes	Yes	Yes
5	IM – S	Yes	Yes	Yes	No	Yes	Yes
6	IM – fungicide 9	Yes	Yes	Yes	Yes	No	Yes
7	IM – fungicide 10.5.1	Yes	Yes	Yes	Yes	Yes	No
8	Traditional management (TM)	No	No	No	No	No	No
9	TM + high SR	Yes	No	No	No	No	No
10	TM + high N	No	Yes	No	No	No	No
11	TM + split-N	No	No	Yes	No	No	No
12	TM + S	No	No	No	Yes	No	No
13	TM + fungicide 9	No	No	No	No	Yes	No
14	TM + fungicide 10.5.1	No	No	No	No	No	Yes

† High seeding rate of 4.94 million seeds ha^{-1}

‡ High N rate consisted of 120% of recommended rate in the Tri-State Fertilizer Guide

§ Split N consisted of 25% of N applied at Feekes 3-4 and the remainder at Feekes 5-6

¶ S fertilizer (gypsum) applied at 17.9 kg S ha^{-1} at Feekes 5-6

Foliar fungicide applied at a rate of 584 mL ha^{-1} at Feekes 9

†† Foliar fungicide applied at a rate of 292 mL ha^{-1} at Feekes 10.5.1

Prior to grain harvest, a straw sample was collected from each plot to estimate straw yield. During harvest the grain yield, moisture, and test weight was recorded by the plot combine and used to calculate grain yield adjusted to 13.5% moisture content. After harvest, the grain was analyzed for the vomitoxin, deoxynivalenol (DON), which is commonly tested for by grain elevators and end-users.

Using this data a spreadsheet was developed to estimate the return on investment for the IM and TM as well as each treatment. Partial economic returns were calculated by subtracting treatment costs and estimated price discount from the gross income. Gross income was calculated by multiplying grain and straw yield by $5.10 per bushel and $120 per ton for this example. Treatment costs varied by location due to different N rates but was calculated by multiplying the input rate per acre by the input cost per unit to estimate the treatment cost per acre. Input prices used in this example were $0.031 per 1000 seeds, $240 per ton of UAN (28% N), $245 per ton of gypsum (16% S), $87.50 per gallon of Feekes 9 fungicide, $301 per gallon of Feekes 10.5.1 fungicide, $7 per acre of liquid product application (N and fungicides), $7.50 per acre of dry product application (S).

In the scenario analyzed in this study, prices for grain, straw, N, and seed were taken from the 2020 Ohio State Extension Wheat Production Budget (https://farmoffice.osu.edu/farm-management/enterprise-budgets), sulfur and fungicide prices were averaged from three different Ohio agricultural retailers, and applications costs came from the 2020 Ohio State Extension Custom Farm Rates Survey (https://farmoffice.osu.edu/farm-mgt-tools/custom-rates-and-machinery-costs). A typical dockage schedule was developed by taking the median values from a number of Ohio grain elevators and end-users; this was used to estimate price deduction for each treatment based on moisture, test weight, and DON concentration. More information on economic returns can be found in Supplemental File 1.

3.3. Example Scenario

The results of this study can be used as an example of a typical scenario where a farmer may be deciding between IM or TM. In this case, yield was significantly increased at three of the four site-years in this study by IM (Table 10). At WARS, the IM increased grain yield both years by an average of 12.3 bushels per acre. At NWARS, 2021 was the only year that the IM significantly increased grain yield, by 12.7 bushels per acre. When the individual removal or addition of a treatment is analyzed separately, it becomes apparent that the use of a fungicide at WARS was important for protecting wheat from disease and thus improving yield. Based on this scenario, the use of a fungicide at flowering (Feekes 10.5.1) appears to be more important than at flag leaf (Feekes 9). The addition of a foliar fungicide at flowering to the TM significantly increased grain yield by 11.8 and 7.7 bushels per acre in 2020 and 2021 respectively. Likewise, the removal of a fungicide at flowering from the IM resulted in a decrease in yield by 6.9 bushels per acre in 2020 and a significant decrease of 9.4 bushels per acre in 2021. Additionally, the use of a fungicide to protect the flag leaf (at approximately Feekes 9) may be beneficial in years when the early to mid-season foliar disease pressure is high. In this study, in 2020 at WARS, the foliar disease pressure was high during the middle of the growing season, resulting in removal of the fungicide at flag leaf from the IM and the addition of the fungicide at flag leaf from the TM significantly changing yield by -10.7 and 12.1 bushels per acre respectively.

Table 10. Average grain yield by site-year for example scenario. Average yield shown for IM and TM and change in yield from IM or TM shown for all other treatments, respectively.

	2020		2021	
Treatment	WARS†	NWARS‡	WARS	NWARS
	--------------------------Bushels per acre		------------------------	
Intensive Management (IM)	73.5	94.4	113.3	108.7
IM - High SR§	-1.2	-1.2	+0.2	-3.0
IM - High N	-2.7	-11.3	-1.5	-3.5
IM - Split N	-0.2	-3.4	-4.2	-6.5*
IM - S	-1.2	+2.7	-4.0	+0.6
IM - Fungicide 9	-10.7*	-3.1	-0.4	-1.7
IM – Fungicide 10.5.1	-6.9	-7.9	-9.4*	-1.1
Traditional Management (TM)	63.9	97.6	98.4	96.0
TM + High SR#	-7.5	-6.1	+1.0	+2.0
TM + High N	+6.6	-10.8	+0.7	+2.0
TM + Split N	-2.9	-6.4	+3.0	+4.4
TM + S	-4.6	-3.4	+0.4	-0.1
TM + Fungicide 9	+12.1*	-0.4	+3.4	+3.1
TM + Fungicide 10.5.1	+11.8**	-15.6	+7.7*	+3.7
IM vs TM	+9.6*	-3.1	+14.9***	+12.7***

* Significantly different at $\alpha \leq .05$ using single degree of freedom contrasts.
** Significantly different at $\alpha \leq .01$ using single degree of freedom contrasts.
*** Significantly different at $\alpha \leq .001$ using single degree of freedom contrasts.
† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
§ Yield values of IM minus input are reported as change in yield from IM treatment.
# Yield values of TM plus input are reported as change in yield from TM treatment.

Although the IM significantly improved grain yield at many of the site-years in this scenario it failed to increase the economic returns at any site-year (Table 11). Although the addition or removal of individual treatments did result in significant yield effects in some site-years, the results were not consistent (Table 11). This suggests that for the prices evaluated in this scenario, neither the complete IM system nor additional inputs individual justify the higher cost of production associated with using them.

Table 11. Average partial returns by site-year for example scenario. Average partial returns shown for IM and TM and change in returns from IM or TM shown for all other treatments respectively.

	2020		2021	
Treatment	WARS†	NWARS‡	WARS	NWARS
	-------------------------USD ha^{-1}-----------------------------			
Intensive Management (IM)	$ 1,471.61	$ 1,720.81	$ 2,255.44	$ 2,088.22
IM - High SR§	$ 80.70	$ 88.67	$ 131.76	$ 4.35
IM - High N	-$ 30.26	-$ 242.91	$ 31.96	$ 15.15
IM - Split N	$ 133.40	- $101.19	$ 60.69	-$ 152.75
IM - S	$ 133.40	$ 89.96	$ 166.89	-$ 64.64
IM - Fungicide 9	$ 156.38	-$ 118.62	$ 26.43	$ 54.68
IM - Fungicide10.5.1	$ 125.94	-$ 118.62	$ 52.92	$ 131.88
Traditional Management (TM)	$ 1,596.31	$ 2,033.68	$ 2,080.03	$ 2,016.57
TM + High SR#	$ 22.01	-$ 208.55	-$ 18.50	-$ 8.15
TM + High N	$ 97.09	-$ 366.93	-$ 137.16	$ 74.92
TM + Split N	$ 30.13	-$ 231.02	$ 322.25*	$ 153.13
TM + S	$ 63.59	-$ 139.91	-$ 3.78	$ 55.05
TM + Fungicide 9	$ 73.80	-$ 119.04	$ 33.45	$ 12.82
TM + Fungicide 10.5.1	$ 103.11	-$ 400.32*	$ 135.67	$ 112.31
IM vs TM	-$ 124.70	-$ 312.87	$ 175.41	$ 71.65

* Significantly different at $\alpha \leq .05$ using single degree of freedom contrasts.
† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH
§ Partial returns of IM minus input are reported as change in yield from IM treatment.
# Partial returns of TM plus input are reported as change in yield from TM treatment.

3.4. Conclusion

The spreadsheet based tool developed from this study can allow farmers to make better informed decisions about the return on investment from certain inputs used in wheat production. In the price scenario evaluated in this study, high intensity management has the potential to increase grain yield but fails to do so economically. Although, as wheat grain or straw prices fluctuate and the price of inputs and application costs change the economic returns of each treatment will change. Therefore farmers should consider their local prices and costs when making decisions to use an input. Farmers can use the return on investment tool found here: Wheat ROI Calculator to estimate the affects of the inputs in this study on their economic returns by editing the file to include their expected grain and straw yield, as well as local input and applications costs. This tool will allow farmers to make more educated and profitable decisions when raising wheat.

Additionally, the field study used to develop this tool showed that the use of individual inputs may increase yield if weather conditions, soil properties, or other factors are yield limiting. Therefore farmers should scout their fields for foliar disease and nutrient deficiencies, monitor weather conditions during the growing season, and used disease modelling tools such as www.wheatscab.psu.edu to identify if conditions are or may become yield limiting. If conditions are yield limiting than the application of an input may be beneficial. This approach of crop scouting and monitoring changing weather and soil conditions combined with using the return on investment tool found here: Wheat ROI Calculator can allow a farmer to make more informed cropping decisions and improve their bottom line.

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Appendix A. Supplemental Tables

Supplemental Table 1. Soil physical and chemical properties at the Western and Northwest Agricultural Research Station for each year.

		Soil Test†							
		OM	P	K	Mg	Ca	pH	Buffer pH	CEC
		%	-----------mg kg^{-1}----------						meq/100g
WARS‡	2020	3.4	118	210	377	1702	5.4	6.6	17.0
	2021	2.8	140	156	444	2124	6.3	6.8	17.1
NWARS*	2020	4.3	51	211	430	3007	6.3	6.7	22.8
	2021	3.6	47	214	414	3198	6.6	6.9	21.2

† OM, organic matter; P, phosphorus (Mehlich 3); K, potassium (Mehlich 3); Mg, magnesium (Mehlich 3); Ca, calcium (Mehlich 3); CEC, cation exchange capacity
‡ Western Agricultural Research Station
* Northwest Agricultural Research Station

Supplemental Table 2. Average nitrogen and sulfur analysis of flag leaf samples collected at Feekes 10.5 for each treatment by site-year.

	Nitrogen				Sulfur			
	2020		2021		2020		2021	
Treatment	W†	NW‡	W	NW	W	NW	W	NW
	------------g kg^{-1}----------				-----------g kg^{-1}------------			
Intensive Management (IM)	40	40	42	41	2.8	3.4	3.6	3.5
IM - High SR	39	40	42	41	3.1	3.5	4.2	3.5
IM - High N	38	37	40	42	2.8	3.0	3.6	4.0
IM - Split N	38	38	45	43	2.7	3.2	4.3	3.9
IM - S	38	39	40	43	2.7	3.1	3.0	3.9
IM - Fungicide 9	39	37	42	44	3.0	3.2	3.7	4.6
IM - Fungicide10.5.1	37	37	43	41	2.8	3.1	4.1	3.9
Traditional Management (TM)	37	38	42	43	2.7	3.1	3.2	4.4
TM + High SR	37	37	38	41	2.7	2.8	2.7	3.9
TM + High N	38	37	41	42	2.7	2.9	2.9	3.8
TM + Split N	39	37	41	41	2.8	2.9	3.2	3.8
TM + S	36	36	44	44	2.6	3.0	4.2	4.5
TM + Fungicide 9	37	37	42	42	2.7	2.8	3.2	3.7
TM + Fungicide 10.5.1	38	36	41	41	2.7	2.8	3.1	3.1

† Western Agricultural Research Station, South Charleston, OH
‡ Northwest Agricultural Research Station, Custar, OH

Supplemental Table 3. Average flag leaf foliar disease and Fusarium head blight (FHB) severity and incidence for each treatment at the Western Agricultural Research Station for each year.

	Flag Leaf Foliar Disease			
	2020		2021	
	Total Disease Incidence†	Total Conditional Severity‡	Total Disease Incidence	Total Conditional Severity
	---------------------------	%	---------------------------	
Intensive Management (IM)	12.0	5.0	13.3	1.1
IM - High SR	11.3	4.3	14.8	1.1
IM - High N	11.5	5.0	17.5	1.2
IM - Split N	7.8	4.3	12.3	1.0
IM - S	8.3	3.8	15.8	1.5
IM - Fungicide 9	9.0	3.5	9.3	0.9
IM – Fungicide 10.5.1	7.3	3.8	14.0	1.0
Traditional Management (TM)	10.0	4.5	13.3	1.4
TM + High SR	12.0	4.3	21.3	1.2
TM + High N	9.8	5.0	8.8	0.8
TM + Split N	10.0	4.0	12.5	1.0
TM + S	13.5	3.8	10.5	0.8
TM + Fungicide 9	8.5	4.3	12.5	1.1
TM + Fungicide 10.5.1	9.8	4.0	12.5	1.6

	Fusarium Head Blight			
	2020		2021	
	FHB Incidence§	FHB Conditional Severity¶	FHB Incidence	FHB Conditional Severity
	---------------------------	%	---------------------------	
Intensive Management (IM)	9.8	6.4	0.3	2.5
IM - High SR	1.3	13.4	0.3	3.8
IM - High N	5.0	2.7	0.0	0.0
IM - Split N	7.5	7.7	1.0	4.1
IM - S	4.0	2.7	0.3	2.5
IM - Fungicide 9	6.5	7.7	0.3	1.5
IM – Fungicide 10.5.1	8.8	14.5	0.3	0.1
Traditional Management (TM)	5.8	0.8	0.5	0.2
TM + High SR	2.0	3.9	0.0	0.0
TM + High N	2.3	7.5	0.5	3.7
TM + Split N	2.3	12.9	0.5	1.5
TM + S	1.3	0.8	0.5	0.6
TM + Fungicide 9	3.0	4.3	0.3	2.5
TM + Fungicide 10.5.1	9.3	7.9	0.0	0.0

Continued

Supplemental Table 3 continued

† Mean number of flag leaves affected by foliar disease
‡ Mean percent leaf area affected on diseased leaves
§ Mean number of spikes affected by Fusarium head blight (FHB)
¶ Mean percent of spikelets affected by Fusarium head blight (FHB)

Supplemental Table 4. Average flag leaf foliar disease and Fusarium head blight (FHB) severity and incidence for each treatment at the Northwest Agricultural Research Station for each year.

	Flag Leaf Foliar Disease			
	2020		2021	
	Total Disease Incidence†	Total Conditional Severity‡	Total Disease Incidence	Total Conditional Severity
	-----------------------------%----------------------------			
Intensive Management (IM)	28.8	5.5	87.5	7.5
IM - High SR	39.0	6.5	74.5	5.5
IM - High N	41.0	6.5	92.5	9.8
IM - Split N	41.5	6.3	97.5	11.9
IM - S	41.5	6.3	92.3	8.5
IM - Fungicide 9	28.0	5.0	39.3	1.4
IM – Fungicide 10.5.1	39.8	6.3	85.0	9.1
Traditional Management (TM)	32.0	5.3	38.5	1.6
TM + High SR	23.8	5.0	30.8	1.5
TM + High N	25.0	5.3	50.8	1.9
TM + Split N	28.8	5.3	54.0	1.4
TM + S	28.8	5.3	47.5	1.5
TM + Fungicide 9	38.5	6.8	92.5	10.2
TM + Fungicide 10.5.1	34.0	5.8	42.3	1.4
	Fusarium Head Blight			
	2020		2021	
	FHB Incidence§	FHB Conditional Severity¶	FHB Incidence	FHB Conditional Severity
	-----------------------------%----------------------------			
Intensive Management (IM)	1.0	0.0	0.3	1.5
IM - High SR	0.0	0.0	0.3	3.5
IM - High N	0.8	0.0	0.0	0.0
IM - Split N	0.0	0.0	0.0	0.0
IM - S	0.5	0.0	0.3	0.2
IM - Fungicide 9	0.5	0.0	0.3	0.1
IM – Fungicide 10.5.1	1.5	0.0	0.5	4.0
Traditional Management (TM)	0.8	0.0	0.5	0.8
TM + High SR	0.3	0.0	0.8	3.9
TM + High N	0.8	0.0	0.5	0.2
TM + Split N	0.8	0.0	0.3	3.8
TM + S	1.3	0.0	0.8	3.8
TM + Fungicide 9	1.3	0.0	0.3	0.3
TM + Fungicide 10.5.1	0.8	0.0	0.0	0.0

Continued

Supplemental Table 4 continued

† Mean number of flag leaves affected by foliar disease
‡ Mean percent leaf area affected on diseased leaves
§ Mean number of spikes affected by Fusarium head blight (FHB)
¶ Mean percent of spikelets affected by Fusarium head blight (FHB)

Supplemental Table 5. Average tillers m^{-1} for each treatment counted in the fall and spring for each site-year.

	Fall†				Spring‡			
	2020		2021		2020		2021	
Treatment	W§	NW#	W	NW	W	NW	W	NW
	----------tillers m^{-2}----------				----------tillers m^{-2}----------			
Intensive Management (IM)	353	308	585	359	x¶	x	1218	1397
IM - High SR	248	255	460	283	x	x	1351	1294
IM - High N	412	314	568	360	x	x	1327	1408
IM - Split N	410	287	594	403	x	x	1292	1314
IM - S	469	331	562	347	x	x	1404	1502
IM - Fungicide 9	406	308	733	393	x	x	1486	1460
IM - Fungicide10.5.1	307	327	545	356	x	x	1328	1358
Traditional Management (TM)	274	234	472	288	x	x	1015	1110
TM + High SR	380	317	564	400	x	x	1357	1381
TM + High N	295	250	492	310	x	x	1069	1089
TM + Split N	311	240	498	254	x	x	1301	1205
TM + S	254	238	466	287	x	x	1232	1233
TM + Fungicide 9	283	252	455	274	x	x	977	1156
TM + Fungicide 10.5.1	294	248	509	285	x	x	1175	1351

† Fall tiller count was conducted at Feekes 1 growth stage.
‡ Spring tiller count was conducted at Feekes 5 growth stage.
§ Western Agricultural Research Station, South Charleston, OH
# Northwest Agricultural Research Station, Custar, OH
¶ Spring tiller counts were not conducted in 2020 due to Covid-19.