Evaluating alternative fertilisers and their impact on yield and quality of spelt and rye under different management systems

Thesis submitted for the degree of Doctor of Philosophy by

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ABSTRACT

Spelt (*Triticum spelta*) and rye (*Secale cereale*) are low-input cereals attracting growing interest as sustainable and nutritionally beneficial alternatives to modern wheat (*Triticum aestivum*). The effects of fertiliser type, fertiliser rate and variety choice on spelt and rye crop yield and quality were assessed in single-site field trials in the 2014-15 and 2015-16 seasons. The multi-factorial trials at Nafferton Farm in Northumberland evaluated four varieties (including both landraces and modern varieties) each of spelt and rye grown with four fertiliser N input types (farm yard manure compost, cattle slurry, mineral N and biogas digestate) at two rates of N (50 and 100 kg/ha).

Farmer Participatory trials took place across 10 farms (4 conventional and 6 organic) in Northeast England during the 2016-17 and 2017-18 seasons. The same four varieties of spelt and rye were evaluated under individual farm management systems and two fertiliser input types (biogas digestate and ‘typical’ farm inputs). Data collection was supported by the creation of an online database and web platform for data recording and subsequent statistical analysis.

In the Nafferton field trials, biogas digestate was the highest yielding fertiliser treatment for spelt (3.64 t/ha) while digestate (5.27t/ha) and mineral N (5.21 t/ha) were the highest yielding N treatments for rye. Yields were significantly higher for both crops in 2015 (spelt: 3.60t/ha; rye: 5.74t/ha) compared to 2016 (spelt: 2.86 t/ha; rye: 3.74t/ha) due to higher solar radiation from April to July. The highest yielding varieties were the spelt landrace Oberkulmer Rotkorn (3.74 t/ha) and the modern rye variety Elias (5.59 t/ha). Rye was not susceptible to foliar disease but yellow rust was present in the spelt and was significantly higher in the spelt x wheat cross Filderstolz. Grain quality parameters (Hagberg Falling Number, specific weight and protein content) varied significantly by variety and year.

In the Farmer Participatory trial, conventional farms (spelt: 3.15t/ha; rye: 3.68t/ha) produced higher yields than organic farms (spelt: 2.18t/ha; rye: 2.23t/ha). Biogas digestate inputs produced higher yields (spelt: 2.68t/ha; rye: 3.70t/ha) than typical farm inputs on both organic and conventional farms. Oberkulmer Rotkorn (2.72t/ha) and Elias (3.76t/ha) were the highest yielding spelt and rye varieties in the multi-site trial.

Across both the factorial field trial and Farmer-Participatory trial, the same spelt (Oberkulmer Rotkorn) and rye (Elias) varieties produced the highest yields while biogas digestate produced higher yields than all other fertiliser inputs except mineral N.

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LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
AHDB	Agriculture and Horticulture Development Board
AUDPC	Area Under the Disease Progress Curve
BD	Biogas digestate (fertiliser input)
CS	Cattle slurry (fertiliser input)
CSS	Cascading Style Sheets
Dank	Dankowskie Amber (rye variety)
DEFRA	Department for Environment Food & Rural Affairs
Fild	Filderstolz (spelt variety)
FPT	Farmer Participatory trial
FYM	Farm yard manure (fertiliser input)
GHG	Green house gas
GS	Growth Stage
GW	Green waste (fertiliser input)
HFN	Hagberg Falling Number
HI	Harvest Index
HMC	HealthyMinorCereals
HTML	Hypertext Markup Language
IPCC	Intergovernmental Panel on Climate Change
KTP	Knowledge Transfer Partnership
MN	Mineral nitrogen (fertiliser input)
NABIM	National Association of British and Irish Flour Millers
NEFG	Nafferton Ecological Farming Group
NFT	Nafferton farm field trial
NUE	Nutrient-use efficiency
Ob Rot	Oberkulmer Rotkorn (spelt variety)
PHP	PHP: Hypertext Preprocessor
RDA	Redundancy analysis
Rub	Rubiota (spelt variety)
Sch	Schlaegler (rye variety)

SIP	Sustainable Intensification research Platform
SPAD	Soil-Plant Analyses Development
SQL	Structured Query Language
TGW	Thousand grain weight
TPC	Total phenolic content
ZOR	Zuercher Oberlaender Rotkorn (spelt variety)

CHAPTER 1.INTRODUCTION

1.1 GOBAL FOOD SECURITY

The current and future pressures of population growth and climate change are major challenges for global food security. The UN estimates that the global population will grow from 7.55 billion people in 2017 to 8.6 billion by 2030 (United Nations, 2017). This continual growth will strain agricultural and ecological resources worldwide and global food demand is expected to increase through to at least 2050 (Tilman *et al.*, 2001; Godfray *et al.*, 2010) with estimates ranging from 70 to 100% more food required by 2050 (Baulcombe *et al.*, 2009), 40% more by 2030 (Beddington, 2010) and a 100-110% crop demand increase from 2005 to 2050 (Tilman *et al.*, 2011). This demand is driven not only by population but also wealth increase, which creates greater consumption of processed food, meat, dairy and fish, placing additional pressure on food-production systems (Tilman *et al.*, 2001; Cassman *et al.*, 2003; Beddington, 2010; Godfray *et al.*, 2010). Beyond population growth pressures, climate change is another factor affecting global food security. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report on the current impacts of global warming and the continuing threat of climate change on sustainable development, including food security (IPCC, 2018). The IPCC warns of climate change increasing poverty and famine in marginalised regions and of yield reductions in major crops, with some impacts already being experienced, especially in vulnerable communities (Hoegh-Guldberg *et al.*, 2018). Global food security will require additional food production from a planet that is already experiencing consequences of over-exploitation, making the task even more daunting.

1.1.1 ECOLOGICAL CONSEQUENCES

The Haber-Bosch process completely transformed global agriculture, leading to extensive and rapid spread of synthetic fertiliser post the 1950’s (Smil, 2001). The most recent estimates predict that total fertiliser demand will reach 202 million tonnes per year by 2020, up from 184 million tonnes in 2015, with N fertiliser demand expected to grow from 110 to 119 million tonnes over the same period (FAO, 2017). The high-yielding variety and intensive fertiliser and pesticide application practices of modern agriculture threaten air, soil and water resources (Mulvaney *et al.*, 2009), which in turn impact ecosystem functions and biodiversity (Hirel *et al.*, 2007). Continued application of large amounts of nitrogen fertiliser leads to eutrophication and manufacture of synthetic fertiliser is energy intensive, reliant on fossil fuels and contributes to greenhouse gas emissions (Vitousek *et al.*, 1997; Raun and Johnson, 1999; Tilman *et al.*, 2002). Since 1970, reactive nitrogen creation increased by 120%, altering the N-cycle with negative consequences for human health and the environment (Galloway *et al.*, 2008). Nitrogen applied as fertiliser that is not used by crops can be lost through volatilisation, denitrification and leaching (Cassman *et al.*, 2002), making crop production the single largest anthropogenic source of reactive N in the global ecosystem, with about 19-26% of N applied to croplands every year ending up in water systems (Smil, 1999). If industrial production trends continue, by 2050 worldwide loss of natural ecosystems to agriculture would be larger than the land area of the United States at 10^9 hectares with 2.4-2.7 times higher nitrogen and phosphorus-driven eutrophication and 2.7 times more pesticide use (Tilman *et al.*, 2001).

Beyond the water-quality effects of industrial agricultural systems, air and climate quality are under threat from industrial production. Combined with forestry and other land uses, agriculture is responsible for ~24% of anthropogenic greenhouse gas (GHG) emissions, primarily through deforestation and emissions from livestock, soil and nutrient management (Smith *et al.*, 2014). The energy-intensive practices of post Green Revolution farming are also reliant on non-renewable resources. The Haber-Bosch process requires natural gas inputs (Smil, 2001) and agricultural reliance on phosphorus is another major concern, with peak phosphorus production predicted to occur around 2030 (Cordell *et al.*, 2009). Population growth and climate change will only continue to strain production systems, especially for the main global crops, including wheat.

1.1.2 WHEAT & FOOD SECURITY

Wheat is the most prolific cereal in the world, with 772 million tonnes produced globally in 2017 (FAOSTAT, 2019). As was the case for agriculture overall, wheat productivity has experienced significant increases since the Green Revolution. The United Nations documented a record high of 2.658 billion tonnes of global cereal production in 2017, which reduced marginally to 2.595 billion tonnes in 2018 (FAO, 2018). The adoption of semi-dwarf, high-yielding varieties along with synthetic fertiliser and crop protection inputs have allowed for unprecedented harvests (Shiferaw *et al.*, 2013), which are deemed necessary to provide for a growing population. The combination of high-fertility/pesticide-demanding cultivars with widespread cultivation has led global wheat production to require massive nutrient inputs. Based on the most recent survey from the International Fertilizer Association, 49.3% of world fertiliser use in 2014 was applied to cereals, and of the 57.3 million tonnes of mineral N applied globally to cereals, wheat received the most of any crop at 18.2% of global fertiliser N use (Heffer *et al.*, 2017). While current wheat production and fertiliser consumption is already massive, annual demand for the cereal is expected to rise by a compound rate of 1.1% per year to 2025 (Cassman *et al.*, 2003) and yields will need to increase at nearly twice the annual rate to meet the demand from a growing population (Shiferaw *et al.*, 2013).

Unfortunately, there is increasing evidence that high-input cereal production practices have met a yield plateau (Calderini and Slafer, 1998; Cassman *et al.*, 2003; Olesen *et al.*, 2011), and climate change is already contributing to declining wheat yield levels in some regions, with production levels predicted to decrease globally by 7-8% (Shiferaw *et al.*, 2013). This is especially the case in areas with long histories of wheat production (including the UK), due to a combination of actual yields approaching yield potential thresholds (Licker *et al.*, 2010; Grassini *et al.*, 2013), changes in agricultural policies (Lin and Huybers, 2012; Ray *et al.*, 2012) and climate change (Lobell *et al.*, 2011; Ray *et al.*, 2012). As pressure to continue to improve wheat yields only grows in the face of global food security, alternatives to high-input systems will need to be employed as industrialised processes become less productive.

Productivity concerns in addressing global food security are exacerbated by evidence of nutrient depletion/dilution in modern cultivars. Agricultural breeding programmes focused on higher-yields largely ignored nutritional quality as a desirable trait, resulting in micronutrient deficiencies in major crops worldwide (Welch and Graham, 1999; Morris and Sands, 2006). Major nutritional deficiencies in wheat have been observed since the Green Revolution, focused primarily on much lower concentrations of zinc and iron in modern cultivars (Fan *et al.*, 2008; Zhao *et al.*, 2009). Breeding for nutritional benefits is considered essential to addressing malnutrition (Welch and Graham, 2004), shifting the focus away from high-input yields. In the face of nutritional dilution, strained resources, ecological consequences, population pressure and climate change, adopting sustainable agricultural practices is not only recommended but essential to ensure future global food and nutrition security.

1.2 SUSTAINABLE INTENSIFICATION

While the Green Revolution was considered a major boon in the progressive development of agricultural systems, the present and future of agriculture is undeniably based in sustainable production. Researchers (Beddington, 2010; Tilman *et al.*, 2011; Shiferaw *et al.*, 2013) and policy experts (Alexandratos and Bruinsma, 2012; Hoegh-Guldberg *et al.*, 2018) are calling for a ‘New’ or ‘Greener’ Revolution to reduce the environmental impacts of agriculture while increasing productivity to meet future global food demands.

Considering the need to produce more food while reducing ecosystem impacts, sustainable intensification has become a focal point of agricultural research. This approach aims to meet population growth demands by increasing food production on existing farmland using practices and technology that place less pressure on the environment and do not undermine future food production capacity (Garnett *et al.*, 2013). Meeting global food demands will require new agricultural systems that combine traditional plant breeding (for nutrient use efficiency and disease resistance) and agronomy (i.e. integrated pest management and crop rotations) with new technology (i.e. precision agriculture and genetic modifications) (Gregory *et al.*, 2002; Tilman *et al.*, 2002; Baulcombe *et al.*, 2009; Beddington, 2010; Godfray *et al.*, 2010). Increasing yields on current croplands will limit biodiversity loss and GHG emissions compared to increasing agricultural land area but relies on increased nitrogen use (Tilman *et al.*, 2011) and while food security pressures require nutrient inputs, more value needs to be paid to agricultural impacts on air and water quality, biodiversity and human health (Vitousek *et al.*, 2009). One of the keys to sustainably meeting future global food demands is improving nutrient-use efficiency (NUE).

1.2.1 IMPROVING NUE

Global cereal production is agriculturally and economically inefficient, with a nitrogen-use efficiency of 33% at the turn of the millennium (Raun and Johnson, 1999). Synthetic nitrogen fertiliser is cheap and accessible, which leads producers to apply extra N with complacency, rather than matching plant needs to fertiliser supply. In the UK, improved fertility management, along with utilising stress-tolerant cultivars and precision technology has shown huge potential to increase NUE at the farm level through a 23% increase in N-use efficiency from 1981 to 2002 (Dobermann and Cassman, 2005). Sustainable crop production will require a multi-faceted approach to improving NUE locally and globally.

A major focus of improving fertiliser-use efficiency is synchronising N supply with N crop requirements (Campbell *et al.*, 1995; Cassman *et al.*, 2002; Tilman *et al.*, 2002; Cassman *et al.*, 2003; Dobermann and Cassman, 2005; Mulvaney *et al.*, 2009). This is relevant to both synthetic fertiliser and organic nutrient inputs, as excess N applications to cropland will end up in air or water resources when supply exceeds crop demand regardless of the source material (Cassman *et al.*, 2002). Additional improvements to NUE can be achieved through crop and variety selection for both modern and ancient genotypes that can accumulate high concentrations of N (Hirel *et al.*, 2007), biologically fix nitrogen (Roy *et al.*, 2002; Drinkwater and Snapp, 2007) and access nutrients in low-input scenarios (Tilman *et al.*, 2002; Drinkwater and Snapp, 2007). Increasing nitrogen-use efficiency of crops would decrease reactive N creation by an estimated 15 million tonnes per year (Dawson *et al.*, 2008) and on-farm adoption of NUE-improving practices could generate savings of 10 million tonnes per year of mineral N fertiliser (Roy *et al.*, 2002). Concern over intensive chemical nitrogen use have also contributed to calls to adopt more organic fertilisers and increase overall waste recycling (Smil, 1999; Roy *et al.*, 2002; Tilman *et al.*, 2002; Cassman *et al.*, 2003; Drinkwater and Snapp, 2007). Farm-yard manures and legume-based green manures have the potential to provide 25% of cropland nitrogen requirements (Roy *et al.*, 2002) and breeding for organic and low-input systems puts an emphasis on sustainable qualities that improve NUE and provide disease resistance, weed suppression and improved nutritional quality characteristics (Dawson *et al.*, 2008).

1.3 GENETIC DIVERSITY

The same forces that contributed to the hyper-productivity of agriculture through industrialised processes also contributed to reductions in genetic diversity of crop species. Part of the challenge in addressing global food security includes the depletion of diverse genotypes and renewed emphasis on sustainable production has drawn attention to landraces as an important genetic resource (Newton *et al.*, 2010). Reincorporating cereal landraces into breeding programmes is expected to offset some of the negative effects of industrial agriculture (Tilman, 1998) and breeders recognise that future productivity is dependent on improving yields in high-stress environments by accessing genetic diversity and collaboration with farmers (Cleveland *et al.*, 1999). As ancient grains, spelt and rye cultivars, including landraces, are considered largely untapped resources of genetic variation.

Landraces have a distinct identity with historical origin and their key characteristic is a lack of formal crop improvement, which contributes to landrace populations being locally adapted and suited to traditional agricultural practices (Villa *et al.*, 2005). Landraces have long been considered a source of breeding pathogen resistance into modern cultivars and are well adapted to low-input fertility (Newton, 2010). The root systems of older wheat genotypes (including landraces) are more developed than modern cultivars, especially semi-dwarf varieties (Siddique *et al.*, 1990; Waines and Ehdaie, 2007) and in N-limited conditions, wheat landraces with lower harvest index result in more nitrogen in the grain than modern cultivars (van Bueren *et al.*, 2010). These adaptations to low-nutrient conditions likely resulted from cultivars outside of high-input breeding programmes growing primarily in marginal and low-input production systems. Beyond agronomic suitability for sustainable agriculture, landraces also demonstrate improved nutrition compared to modern genotypes, including zinc and iron (Monasterio and Graham, 2000), which have both decreased sharply in common wheat since the Green Revolution (Fan *et al.*, 2008; Zhao *et al.*, 2009). The depletion of beneficial agronomic and nutritional characteristics from the global cereals genome contributes to concerns for future global food security and both the scientific and agricultural communities are turning to minor cereals with ancient pedigree as alternatives to modern wheat.

Alternative approaches to agricultural production are required to address the pressures of global population growth and climate change. Sustainable practices need to be developed and more widely adopted to reduce reliance on high-input systems, improve nutrient-use efficiency, develop nutritionally-dense foods and broaden genetic diversity in crops. Major global cereal crops, including wheat, will certainly continue to have a role, but alternative crops will be key fixtures in sustainable production systems. As ancient cereals with long histories in European agriculture and growing consumer interest, spelt and rye are strong candidates for adoption in sustainable agriculture.

1.4 AIMS AND OBJECTIVES

Spelt and rye are considered minor crops in the UK and have not been thoroughly examined for yield and quality characteristics. The overall aim of this PhD project was to evaluate the agronomic and quality performance of spelt and rye varieties for use in sustainable production systems. Toward this aim, the specific objectives of the project were to:

1. Quantify the effects of fertilisation regimes (fertiliser input type and rate) and variety on leaf disease, grain yield, milling quality and nutritional content of spelt and rye grown in factorial field trials at Nafferton farm.
2. Establish a Farmer Participatory research platform comprised of an online database for data collection, reporting and monitoring and a collaborative network for knowledge exchange among growers and researchers in Northeast England.
3. Quantify the effects of fertiliser type, management system and variety on leaf disease, grain yield and milling quality of spelt and rye grown on different organic and conventional farms in Northeast England.

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CHAPTER 2. LITERATURE REVIEW

2.1 SPELT

2.1.1 HISTORY

Spelt (*Triticum spelta*) was among the first hulled wheats domesticated, along with einkorn and emmer, almost 10,000 years ago in the Fertile Crescent (Stallknecht *et al.*, 1996; Arzani and Ashraf, 2017). The grain is suspected to have migrated through trade to Europe, where it was more widely cultivated than it had been in the Middle-East, where emmer dominated (Kema, 1992). Spelt was a primary staple in the UK, along with Europe, where it replaced emmer, and continued to be grown through the majority of the first millennium (Jones, 1981). Spelt is typically considered an old European cultural wheat (Bonafaccia *et al.*, 2000; Bertin *et al.*, 2001; Konvalina *et al.*, 2010) and the primary spelt breeding programmes are based in Europe (Bertin *et al.*, 2001).

Spelt is taller and has longer ears compared to wheat (Winzeler *et al.*, 1993) and as a hexaploid wheat, spelt is likely the ancestor of free-threshing common wheat, although it remains defined by the glumes (hulls) covering seeds even after harvest (Arzani and Ashraf, 2017). The hull protects the grain against disease and storage pests and improves germination (Pospišil *et al.*, 2011; Vuckovic *et al.*, 2013; Arzani and Ashraf, 2017), but it also requires additional processing. Despite wide cultivation, especially in Europe, where it still took up 40% of the Middle-European wheat-growing area in 1930 (Kema, 1992), spelt was easily overshadowed by other major cereals, especially free-threshing wheats, by the time the Green Revolution arrived. De-hulling was not the only factor in the decline of spelt popularity—the ancient grain could not compete with breeding advances of other cereals (Stallknecht *et al.*, 1996), especially as high-yielding common wheat cultivars were developed to thrive in high-input fertility systems (Pearman *et al.*, 1978; Austin *et al.*, 1980; Bell *et al.*, 1995; Foulkes *et al.*, 1998).

Spelt is by far a minor cereal in terms of production compared to the major global (wheat, maize and rice) and European (wheat, barley, maize) cereals, but concerns over sustainable management, genetic diversity and nutritional quality have contributed to renewed interest in the ancient grain in Europe and North America.

2.1.2 AGRONOMY

One of the primary reasons for the growing interest in spelt is its suitability for low-input production systems. With growing concern over global food security compounded with climate change and the ecological consequences of intensive agriculture, spelt, along with other minor grains, is an appealing alternative to resource-intensive wheat production. The same inattention to spelt-specific breeding programmes that led to the hull-wheat becoming a minor crop also positions the grain as a key component in developing low input agricultural systems.

Spelt produces much lower yields compared to wheat, which as noted is largely the result of extensive breeding efforts focused on free-threshing wheat production. In Europe, yields from trial studies range from 1.86 t/ha in Italy (Codianni *et al.*, 1996) to 4.3-6.5 t/ha in Slovakia (Lacko-Bartošová *et al.*, 2010). In the UK, organic spelt is expected to reach 3.5 t/ha, while organic wheat yields are estimated at 4.2 t/ha (Lampkin *et al.*, 2017). As spelt is combine harvested with the hull intact, final yields are reduced 30-35% after processing (Lampkin *et al.*, 2017), further contributing to the yield advantage of common wheat.

2.1.2.1 LOW-INPUT BENEFITS

Despite this productivity difference, spelt is considered particularly well-suited for organic production systems as it remains productive with limited fertility and crop protection inputs and can grow reasonably well in marginal areas (Bonafaccia *et al.*, 2000; Konvalina *et al.*, 2010; Lacko-Bartošová *et al.*, 2010; Pospišil *et al.*, 2011; Escarnot *et al.*, 2012; Arzani and Ashraf, 2017). The grain also has early flooding and cold temperature tolerance compared to wheat (Burgos *et al.*, 2001) and is resistant to diseases common in wheat (Schmid *et al.*, 1994), including yellow rust (Kema, 1992; Kema and Lange, 1992; Konvalina *et al.*, 2010), powdery mildew (Konvalina *et al.*, 2010) and fusarium infection (Wiwart *et al.*, 2004). These adaptations have contributed to breeding efforts to incorporate spelt disease and stress tolerance into modern wheat cultivars (Schmid *et al.*, 1994; Burgos *et al.*, 2001), especially as more and more pesticides are banned through the EU Pesticides Directive (European Parliament, 2009).

Under-low input growing conditions the productivity advantage of modern wheats is often matched or overcome by spelt. When fertilised with either 80 or 110kgN/ha, yield differences between spelt and wheat were not significantly different and at marginal sites, where wheat would not typically be grown, spelt yield was 10.5% higher than wheat (Rüegger and Winzeler, 1993). In a comparison of wheat and spelt grown under different management systems, wheat yields were 47% higher under conventional management but only 17% higher than spelt under organic management (Bavec *et al.*, 2012). Both studies emphasise the ability of spelt to produce in non-optimal scenarios for high yielding wheat production. Although spelt yields have been shown to increase by 10% from optimal N inputs based on site specific conditions (Rüegger and Winzeler, 1993), under high fertiliser inputs (e.g. 200kgN/ha), lodging becomes the primary limiting factor to increased spelt yields (Bertin *et al.*, 2001; Koutroubas *et al.*, 2012).

While wheat clearly has yield advantages over spelt in high-input production systems, sustainable agricultural production systems are looking to reduce ecological impacts by using fewer inputs. In a low-input scenario, spelt becomes a much more attractive alternative to common wheat, and as breeding programmes develop to exploit some of spelt's most advantageous qualities, productivity will only increase over time. Especially as regulations reduce the availability of chemical crop protection methods, the search for greater sources of genetic resistance to major fungal pathogens will become increasingly important, which will increase the role of spelt in future production systems.

2.1.3 CONSUMER INTEREST

Overall, interest in spelt and other alternative grains is associated with consumer preference for value-added products, particularly in relation to health benefits. In the UK, Italy, Finland and Germany, consumer Willingness to Pay (i.e. the maximum price a consumer will pay for a product) for cereal products increased with perceived health benefits (Dean *et al.*, 2007). UK customers are also more willing to pay for wholegrain or wholegrain granary bread products due to perceived health benefits (Hellyer *et al.*, 2012). This interest in 'healthy' cereal products has also extended to ancient grains. In Germany, participants rated ancient grain varieties (including spelt) very highly, perceiving them to be both healthy and environmentally-friendly, and researchers noted that ancient grain bread can compete with organic as a value-added product (Teuber *et al.*, 2016).

Specific preferences for cereal products and how they're processed understandably varies by country based on local accessibility to different commodities. In the UK, enrichment was the preferred method of adding nutrients to grain products while traditional cross-breeding was preferred in other European countries and fermentation was viewed positively in Finland and Germany, likely due to consumer familiarity with each of these methods in their home locale (Dean *et al.*, 2007). The consumer perceptions in German are certainly affected by the wide availability of wholegrain, organic and ancient grain products (Teuber *et al.*, 2016) compared to other areas where white bread is much more common.

2.1.3.1 **BAKING WITH SPELT**

Although spelt is noted for higher protein content than wheat (Abdel-Aal *et al.*, 1995; Codianni *et al.*, 1996; Stallknecht *et al.*, 1996; Abdel-Aal *et al.*, 1997; Bonafaccia *et al.*, 2000; Chrenkova *et al.*, 2000; Bojnanska and Francakova, 2002; Ceglinska, 2003; Moudrý *et al.*, 2011; Escarnot *et al.*, 2012; Filipcev *et al.*, 2013; Longin *et al.*, 2015; Bernas *et al.*, 2016; Arzani and Ashraf, 2017), it produces a wetter, weaker gluten (Wilson, 2008; Moudrý *et al.*, 2011; Filipcev *et al.*, 2013), which affects how it is treated as a bread-making flour (Whitley, 2009; Ginsberg, 2016). The gliadin:glutenin ratio determines gluten's viscoelastic properties and stronger doughs result from lower ratios (Uthayakumaran *et al.*, 1999). This ratio is lower for wheat compared to spelt, which means that spelt dough is stickier than and not as strong as wheat (Pruska-Kedzior *et al.*, 2008; Frakolaki *et al.*, 2018). This affects how the dough is handled and shaped and ultimately affects the final volume and texture of the bread, which is often denser than a typical wheat loaf, especially when prepared in the same manner (Whitley, 2009).

Bread-making quality, including protein and gluten content, vary based on cultivar. Spelt x wheat hybrids have been bred not just to increase yields, but also to improve baking quality (Zanetti *et al.*, 2001), and hybrids demonstrate lower protein, but higher flour extraction and better bread volume and texture than traditional spelt cultivars (Ceglinska, 2003; Sobczyk *et al.*, 2017). Compared to other hulled wheats (mainly einkorn and emmer), spelt has a reasonable gluten index and higher sedimentation values, which indicate that it is suitable for use in value-added bread products (Moudrý *et al.*, 2011), and is capable of meeting similar milling and baking quality specifications of wheat (Zieliński *et al.*, 2007; Korczyk-Szabó and Lacko-Bartošová, 2012; Bernas *et al.*, 2016).

While spelt demonstrates reasonable baking quality characteristics, the success of a final loaf is based on bread-making technique. Spelt is often viewed as producing poorer baking-quality dough compared to wheat in terms of texture and structure, especially based on the Chorleywood Baking Process (Cauvain and Young, 2006), which produces consistent, high-rising breads with white wheat flour. The Chorleywood process was designed to produce a softer bread in less time, using light loves with soft British-grown flour, which has contributed to about 80% of all British bread being made through this process (Rubel, 2016). The high protein and poor gluten properties of spelt flour that are unsuitable for this quick-process are not considered problematic in artisan baking.

The term 'artisan bread' was popularised in the late 1990s/early 2000s to describe unsweetened, unenriched and typically un-yeasted loaves from Europe that stood in stark contrast to soft, white American and British sandwich breads (Rubel, 2016). Interest in sourdough and slow-proving processes that define artisan bread making gained traction as a counter force to the industrial food system and correspond with criticism of intensive agriculture (Whitley, 2009; Rubel, 2016). The UK artisan bread market increased in value by 10.8% from 2009 to 2014 and artisan bread sales are expected to grow from £683 million in 2014 to £781 million in 2019 (CBA, 2014). Artisan baking is currently being adapted to a much wider range of flour types and techniques, including a large influence of wholegrains and wide spectrum of cultivars (Ross, 2018). Wholemeal spelt is valued in artisan, slow-fermentation bread making for its natural yeasts and bacteria which produce a lively sourdough more quickly than wheat flour (Whitley, 2009). Extensive analysis of baking performance highlights that spelt dough is generally more resistant to mechanical processing (as is common with the Chorleywood process), requiring longer development time but demonstrating greater stability, compared to wheat (Sobczyk *et al.*, 2017).

2.1.3.2 **NUTRITIONAL BENEFITS**

Consumption of wholegrains is widely considered nutritionally beneficial, as dietary intake of whole-grain foods is associated with decreased risk of cardiovascular disease, diabetes, obesity and some cancers (Mellen *et al.*, 2008; Bondia-Pons *et al.*, 2009; Okarter and Liu, 2010). Growth in consumer awareness of the nutritional benefits of whole-grain products has led to a renewed interest and higher consumption of cereal grains other than common wheat, including spelt (Stallknecht *et al.*, 1996). Spelt is often consumed as a wholemeal product (Jacobs and Gallaher, 2004), especially as a large proportion of spelt flour is used in artisan baking and is primarily available as wholemeal (Whitley, 2009). As noted, consumers showing a preference for wholegrain bread products also show a Willingness to Pay for perceived health benefits of ancient grains (Teuber *et al.*, 2016), as the nutritional benefits of wholegrain and spelt are considered to go hand-in-hand.

The prevalence of coeliac disease, an autoimmune disorder caused by a reaction to gluten, has increased dramatically in wheat-consuming populations over the past 40 to 50 years (Lohi *et al.*, 2007; Cummins and Roberts-Thomson, 2009; Rubio–Tapia *et al.*, 2009). This change is attributed to life-style shifts (including growth in Western-style diets and early first introduction of wheat products to infants), which ultimately contribute to high-consumption of wheat-based products. There is also evidence that modern wheat breeding practices may contribute to higher exposure to disease inducing gluten proteins (van den Broeck *et al.*, 2010) and there is growing research into non-coeliac gluten sensitivity associated with Irritable Bowel Syndrome and other disorders (Catassi *et al.*, 2013). With this rise in incidence of gluten and other wheat-related intolerance, minor cereals, such as spelt, rye, oats, emmer and einkorn, have generated increasing interest, particularly for use in speciality baking products. As noted previously, spelt contains gluten, which does not make it suitable for individuals with coeliac disease, yet the grain has retained a reputation as a digestible alternative for individuals with wheat intolerance (Stallknecht *et al.*, 1996; Whitley, 2009). There is evidence that spelt bread contains low levels of fructans and total FODMAPs (Fermentable Oligosaccharides, Disaccharides, Monosaccharides and Polyols) compared with other breads, leading to less unabsorbed carbohydrates to disrupt the gastrointestinal system (Biesiekierski *et al.*, 2011).

Overall, wholegrain cereals are considered to contribute considerable amounts of micro and macronutrients, especially iron (Fe), magnesium (Mg) and zinc (Zn), to the human diet (McKevith, 2004). Unfortunately, there is increasing evidence that the focus of intensive agricultural production on yield gains has contributed to lower nutritional-value of modern wheats, including decreased zinc, and to a lesser extent iron, concentrations (Zhao *et al.*, 2009). In an analysis of wheat samples grown in the UK over 150 years, grain zinc, copper (Cu) and magnesium concentrations decreased significantly from 1968 to 2005 and iron concentrations were also 23-27% lower (Fan *et al.*, 2008). This analysis suggested that the decreasing trend was likely due to a dilution effect from increased grain yield and/or harvest index, corresponding with the introduction of short-straw cultivars in wheat breeding programs. An ancient grain with taller stems, spelt has not gone through the same high-yielding breeding programmes of wheat and is considered to have greater grain nutrient capacity as a result.

A range of studies of spelt quality in North America and Europe found that spelt has higher concentrations of zinc than common wheat (Ranhotra *et al.*, 1995; Grela, 1996; Ranhotra *et al.*, 1996a; Piergiovanni *et al.*, 1997; Ruibal-Mendieta *et al.*, 2005; Zhao *et al.*, 2009; Hussain *et al.*, 2010; Suchowilska *et al.*, 2012; Kwiatkowski *et al.*, 2015) and many of those same studies also found higher concentrations of iron in spelt compared with wheat (Ranhotra *et al.*, 1995; Ranhotra *et al.*, 1996a; Ruibal-Mendieta *et al.*, 2005; Zhao *et al.*, 2009; Hussain *et al.*, 2010; Suchowilska *et al.*, 2012; Kwiatkowski *et al.*, 2015). A study focussing exclusively on spelt nutrient content identified 237 spelt varieties with average zinc quantities of more than 50 mg/kg and 139 varieties with greater than 50 mg/kg of iron (Gomez-Becerra *et al.*, 2010), which is indicative of the genetic potential for spelt varieties to produce high concentrations of these micronutrients.

2.2 RYE

2.2.1 HISTORY

Rye (*Secale cereale*) is a member of the grass family, which was first domesticated in what is now Turkey in the Neolithic period (Hillman, 1978; Behre, 1992) and then made its way south into the Fertile Crescent (Sencer and Hawkes, 1980). Archaeological evidence suggests that when hunter-gatherers first started cultivating crops in what is now Syria, rye was among the first wild grasses domesticated, as it was more easily threshed than early wheats and it grew more successfully during a sudden dry, cold climatic period known as 'The Big Freeze' (Hillman *et al.*, 2001). Despite this early cultivation, ancient wheats and barley gained popularity as the Earth warmed and agricultural technology improved.

Rye eventually found favour in Europe about 6,000 years ago (Hillman, 1978; Behre, 1992), especially in areas of Eastern and Northern Europe where it was well suited to the dry, cold climate (Behre, 1992). Even as rye spread, it was considered a 'grain of poverty' and often mixed with wheat to mask its bitter taste (Nuttonson, 1958; Behre, 1992). Despite this preference for wheat and barley, rye cultivation continued to spread, and the crop became increasingly significant in Nordic countries during the Middle Ages because it could grow successfully under previously inhospitable conditions (Alenius *et al.*, 2013). The association of rye with poverty continued through the medieval period, especially North of the Alps, where the nobility preferred wheat while rye fed the masses (Ginsberg, 2016). This reliance on rye has left an indelible mark on Eastern and Northern Europe, where it remains a staple crop, especially in Poland, Germany, western Russia, Belarus and Ukraine, and this extensive use makes it second only to wheat for bread production globally (Bushuk, 2001; Schlegel, 2014).

Despite the popularity of rye in Europe, modern productivity advances for the grain have been behind those of major crops, even in countries where rye is common, as species-specific breeding efforts have not occurred to the same magnitude as for wheat (Peltonen-Sainio *et al.*, 2009). In the primary rye producing countries, rye production decreased by 17% in Germany, 29% in Poland and 2.3% in the USSR from 1961 to 1991, during which time wheat production increased by 227%, 232% and 15% in each country respectively (FAOSTAT, 2019). While growth in wheat production is no longer increasing exponentially as was the case right after the Green Revolution, rye production has continued to decline since the new millennium, with 47%, 45% and 62% declines in Germany, Poland and Russia respectively from 2001-2017 (FAOSTAT, 2019). Despite this decline, rye production has grown in other areas over the past five years, including the United Kingdom, where 50,890 tonnes were harvested in 2017, up from 33,000 tonnes in 2012 (FAOSTAT, 2019). In the UK, rye has traditionally been used for crispbread, and is grown mainly in East, Central and Southern England, often in areas prone to drought (McDonald, 1991).

2.2.2 AGRONOMY

Rye is an exceptionally tall growing crop, with the longest stems of all cultivated small grains and the longest root system of all cereals (Schlegel, 2014). These properties have contributed to the grain being one of the most widely distributed cereals in the world (Bushuk, 1976). Rye is effective on light soils, where it can penetrate deeper soil layers (Nedzinskienė, 2006), under potential drought conditions, as it requires 20-30% less water than wheat per unit dry matter (Schlegel, 2014) and in locations with harsh winter conditions (Bushuk, 2001).

Compared to major cereals, including wheat, rye is better adapted to extreme weather conditions, specifically cold temperatures and dry conditions. Generally, rye is considered a winter-hardy crop and is resistant to winterkill in regions susceptible to prolonged freezing temperatures (Nuttonson, 1958; Bushuk, 1976; Fowler, 1982; Jedel and Salmon, 1994; Webb *et al.*, 1994). Large, deep root systems provide drought resistance, and in years with low rainfall, rye will out-produce other cereal crops (Tupits, 2008).

One of the most cited benefits of rye are its allelopathic properties. Rye proved to be an effective cover crop and mulch to prevent weeds (Putnam *et al.*, 1983) due to phytotoxic compounds in rye shoot and root tissue, which inhibit emergence and seeding growth in other plants (Barnes and Putnam, 1987). Thus far, 16 allelochemicals have been identified in rye (Schulz *et al.*, 2013) and though it is used most often to control weeds as a cover crop (Putnam *et al.*, 1983; Norsworthy *et al.*, 2011; Tabaglio *et al.*, 2013) and mulch (Smith *et al.*, 2011), allelopathic properties are also present when rye is grown as a main crop (Jabran *et al.*, 2015).

2.2.2.1 LOW-INPUT BENEFITS

The primary inputs applied to rye are fungicides, especially against ear disease, and fertiliser, although rye is considered a low-input crop, due to its abilities to resist disease, and utilise nutrients in low fertility environments through its extensive root system (Nuttonson, 1958; Schlegel, 2014).

Rye is one of the least susceptible cereals to leaf disease, which reduces the amount of fungicides applied during the growing season. The primary leaf diseases of concern in rye are powdery mildew (Bushuk, 1976; Bujak and Jurkowski, 2013; Schlegel, 2014) and brown leaf rust (Bushuk, 1976; Skuodiene and Nekrosiene, 2009; Schlegel, 2014). Leaf disease in rye can be controlled with fungicides, but this does not typically lead to a yield increase (McDonald, 1991) and breeding for resistance is also effective (Schlegel, 2014). The main disease concerns for rye occur on the ear, namely ergot, which is considered the most important disease to control for rye production (Nuttonson, 1958; Bushuk, 1976; Schlegel, 2014). While fusarium infection can also cause quality deterioration in rye ears (Kulik *et al.*, 2015; Papouskova *et al.*, 2015), ergot is toxic to humans and animals (Barger, 1931) and rye containing 0.5% or more of ergot is considered unfit for food or feed (Schlegel, 2014), which can cause substantial economic losses. While pesticides applications are effective, they are not economical, and similar to leaf disease management, rotations and breeding for resistance are often considered more reasonable management strategies for ergot than high crop protection inputs (Bushuk, 1976; Schlegel, 2014).

Rye is better adapted to middle and low-rate soil fertility and is less sensitive to poor nutrient supply than wheat (Deike *et al.*, 2008) and has higher nitrogen-use efficiency than both wheat and barley (Schlegel, 2014). Rye crops do benefit from fertiliser inputs, reaching higher yields with mineral NPK fertilisers (Budzyński *et al.*, 2003; Nedzinskienė, 2006; Gollner *et al.*, 2011; Schlegel, 2014; Stepień *et al.*, 2016) and experiencing increases from organic fertility sources (Gollner *et al.*, 2011). While rye experiences a yield bump from fertilisation, nitrogen requirements are lower than for wheat (McDonald, 1991) and yield increases diminish or are negligible beyond the optimum fertiliser rate (Budzyński *et al.*, 2003; Nedzinskienė, 2006). Additionally, leaf disease, especially of powdery mildew, has been shown to increase with higher fertility applications, as excessive nitrogen inputs can weaken plant resistance (Bushuk, 1976). Reduced fertility recommendations for rye are also partially due to lodging risk. As a tall-growing cereal, rye is considered susceptible to lodging (McDonald, 1991). However, this is not completely driven by plant height or fertility—precipitation is often the driving factor determining lodging in rye (Peltonen-Sainio *et al.*, 2002).

2.2.3 CONSUMER INTEREST

2.2.3.1 BAKING WITH RYE

Rye protein is the lowest among cereals (Schlegel, 2014), and has a comparatively higher proportion of water and salt soluble protein, which does not perform the same in typical bread-making processes for wheat (Bushuk, 1976). Additionally, rye is susceptible to pre-harvest germination (sprouting) and high alpha-amylase activity (Bushuk, 1976; McDonald, 1991;

Schlegel, 2014), which impacts grain quality, especially Hagberg Falling Number, an indicator of final bread structure (NABIM, 2014). These properties mean that as a flour, rye reacts very differently than wheat and the bread-making processes for these grains have been adapted differently over time. Compared with the standardised commercial wheat-based bread products made easily and consistently through the Chorleywood Bread Process (Cauvain and Young, 2006), rye bread-making is much more varied and diverse.

The emphasis on shape and texture typical of white wheat loaves give way to texture and flavour in most rye bread, which is often focused on slow-fermentation and whole grains (Ginsberg, 2016). Sourdough fermentation helps activate proteins in rye (Schlegel, 2014), the acid dough created by this process inhibits excessive alpha-amylase activity and sourdough allows the dough to adsorb more water, creating a softer dough that allows rye bread to keep better after baking (Whitley, 2009; Ginsberg, 2016).

2.2.3.2 **NUTRITIONAL BENEFITS**

The same properties that contribute to the preferential use of rye in artisan baking processes also draw consumer interest for nutritional benefits. Rye products are rich in fibre, lower in gluten content and have higher nutritional value (including high iron) compared to wheat, especially because it is commonly consumed as a wholegrain (Schlegel, 2014). The nutritional benefits of consuming wholegrains, especially for cardiovascular health (Jacobs and Gallaher, 2004), are widely documented and discussed earlier in this chapter (Section 2.1.3.2). Rye is among the cereals most commonly associated with these benefits because it is often consumed as a wholegrain, both as a flour and whole kernel (Jacobs and Gallaher, 2004). Especially in sourdough bread-making, building a rye sour culture from wholegrain rye flour is highly recommended to contribute naturally occurring yeast and lactic-acid producing bacteria to the fermentation process (Ginsberg, 2016). Many traditional rye breads are described as ‘black’ due to wholegrain flour use (Nuttonson, 1958; Schlegel, 2014) and this preference for unprocessed flour adds to the nutritional benefits of rye products.

Rye is considered a good source of dietary fibre, especially as a wholegrain, which can have a positive impact on human health. Analyses of different small grain cereals found wholegrain wheat and rye to have the highest dietary fibre (Slađana *et al.*, 2011) and while total dietary fibre is similar between the two cereals, the composition of rye and wheat fibre is different (Kamal-Eldin *et al.*, 2009). Dietary studies have found that high-fibre rye consumption reduces serum cholesterol in hamsters (Zhang *et al.*, 1994) and was later demonstrated in men (Leinonen *et al.*, 2000). An Australian study of adult males found high-fibre rye and wheat consumption improved bowel and metabolic health markers and rye fibre was more effective than wheat in increasing overall health markers (McIntosh *et al.*, 2003).

Beyond dietary fibre, rye is also cited as a source of beneficial nutrients, especially as an alternative to common wheats that have become increasingly less nutrient-rich through industrialised production. As with all cereals, rye nutritional content varies based on management and environmental conditions, but it has been demonstrated to have higher potassium (Kowieska *et al.*, 2011; Rodehutscord *et al.*, 2016), iron (Kowieska *et al.*, 2011; Schlegel, 2014) and zinc content (Jorhem and Slanina, 2000; Kowieska *et al.*, 2011) compared to wheat. As an ancient grain, rye is considered a useful alternative to high-yield/low-nutrient breeds of cereals, especially in sustainable production systems for global food security.

Contrary to many consumer perceptions, rye does contain gluten, but rye gluten is not particularly strong (Schlegel, 2014), which contributes to interest in rye products in the gluten-intolerance market. As noted, rye is lower and weaker in protein than wheat, limiting a rye dough's ability to form gluten (Ginsberg, 2016), which not only affects texture and shaping but also digestion properties. A dietary study with men and women found that when they consumed rye kernel bread (containing whole rye kernels as well as flour) in their evening meal, their glycaemic regulation, metabolic gut hormones and appetite regulation improved (Sandberg *et al.*, 2016). Consuming products with whole-grain rye improved gut microbiota diversity in rats (Ounnas *et al.*, 2016) and healthy adults experienced improved bowel functions when consuming whole-meal rye bread (Gråsten *et al.*, 2000). While rye is not gluten-free, these dietary studies demonstrate the potential digestive and gut-health benefits of consuming rye. As more and more people are turning to alternatives to processed-wheat products as a result of gluten and/or wheat intolerance, rye is considered a healthy and digestible option.

2.3 ORGANIC VS CONVENTIONAL AGRICULTURE

As low-input crops, both spelt and rye (especially spelt) are often recommended for organic production systems. While there are questions about the ability of organic agriculture to solely provide future global food demands, organic management strategies (especially relating to nutrients) are often included in discussion of improving agricultural sustainability (Refsgaard *et al.*, 1998; Smil, 1999; Tilman *et al.*, 2002; Cassman *et al.*, 2003; Drinkwater and Snapp, 2007; Dawson *et al.*, 2008; Tambone *et al.*, 2010; Seufert *et al.*, 2012). At the same time, the imposing demands of increased productivity required for future global food security are often conventionally focused. While there is an acknowledged role for organic methods, there are also concerns over lower yields based on lower nitrogen content and synchronising inputs with plant demand (Fixen and West, 2002; Tilman *et al.*, 2002; Mäder *et al.*, 2007; Bilsborrow *et al.*, 2013). Globally, organic yields are lower than conventional yields (around 20%), with variation based on site and system characteristics (De Ponti *et al.*, 2012; Ponisio *et al.*, 2015). When best organic practices are applied, organic yields are 13% lower than conventional, while the typical discrepancy is 34% when the two systems are most comparable (Seufert *et al.*, 2012).

2.3.1 FERTILITY

Current industrial cereal production was developed to maximise yields under high fertiliser input conditions. Modern wheat cultivars are most productive under conventional management systems, where synthetic nutrient inputs are synchronised to meet crop demand. In comparisons of wheat grown in organic and conventional farming systems in the UK, conventional fertility results in higher yields, correlated with higher leaf nitrogen content (Jones *et al.*, 2010; Bilsborrow *et al.*, 2013; Rempelos *et al.*, 2018). In particular, modern wheat cultivars demonstrate an improved ability to take up mineral nitrogen compared to soil nitrogen, likely as a result of breeding selection for synthetic inputs (Jones *et al.*, 2010).

The agronomic advantage of conventional agriculture does not come without consequences. As outlined in the introduction, excessive conventional fertiliser inputs have significant environmental consequences, including eutrophication, biodiversity loss and GHG emissions (Tilman *et al.*, 2002) and industrial cereal production with high-input cultivars appears to be reaching a yield plateau (Calderini and Slafer, 1998; Cassman *et al.*, 2003; Olesen *et al.*, 2011). While conventional fertility still has productivity benefits over organic, the apparent yield stagnation and acknowledged ecological consequences of the high-input approach emphasised since the Green Revolution have led to renewed interest in improving the productivity of organic and low-input production systems.

The benefits of organic agriculture are primarily attributed to environmental sustainability and, more recently, nutritional value, especially compared to conventional management. In comparisons of ecological impacts, organic agriculture has higher levels of biodiversity markers (Bengtsson *et al.*, 2005; Hole *et al.*, 2005; Mondelaers *et al.*, 2009; Tuomisto *et al.*, 2012), reduced contribution to GHG emissions and carbon footprints (Tuomisto *et al.*, 2012; Lee *et al.*, 2015) and improved soil quality, including carbon and organic matter levels and biological activity (Mondelaers *et al.*, 2009; Gattinger *et al.*, 2012; Tuomisto *et al.*, 2012) than conventional farming. Organic production is also increasingly recognised as beneficial nutritionally, with higher levels of antioxidants, lower cadmium and reduced pesticide residues (Barański *et al.*, 2014). While these benefits are all important considerations in future agricultural sustainability, improving the efficacy of organic fertiliser inputs remains a challenge.

Organic soil fertility management is based on long-term, integrated approaches rather than short-term, specific practices of conventional agriculture. Organic nutrient supply relies on leguminous crops, leys, rotations and recycling of nutrients through composted and un-composted manures (Berry *et al.*, 2002; Watson *et al.*, 2002). While organic fertility sources have the potential to supply a large amount of available N, slow mineralisation of organic sources does not synchronise with crop demand, preventing optimal use of available nitrogen (Berry *et al.*, 2002). Manure, crop residues and leguminous leys do not supply as much plant-available nitrogen as synthetic fertilisers (Berry *et al.*, 2002), but the timing of nutrient availability is the major challenge in organic production. The same slow-release, soil stable properties of organic composts and clover leys valued for reduced risk of leaching and ecological impacts (Tilman *et al.*, 2002) result in a temporal mismatch between soil mineralisation of nitrogen and crop demand (Pang and Letey, 2000; Mäder *et al.*, 2007). Yields can be increased in organic systems via breeding for improved NUE and improved fertilisation management (Seufert *et al.*, 2012; Ponisio *et al.*, 2015). Efforts to increase productivity in organic agriculture have also included developing and adapting higher mineral-content fertilisers, and one of the most promising is biogas digestate.

2.3.2 BIOGAS DIGESTATE

Anaerobic Digestion (AD) is a controlled microbial process, which in the absence of oxygen, breaks down organic matter to produce methane and carbon dioxide biogas as well as fertile digestate (Chynoweth *et al.*, 2001; Tani *et al.*, 2006). AD supplies renewable energy, recycles waste materials, reduces greenhouse gas emissions and stores carbon (Tambone *et al.*, 2010) and is growing in popularity, with more than 400 plants currently in the UK outside of the water industry (NNFCC, 2018). The digestate resulting from the AD process is a potent fertiliser and is considered a valuable recycled fertility source for both organic and conventional production systems.

Nutrient composition of digestates vary based on source material and process parameters/conditions, but they have higher amounts of ammonium and available nitrogen than animal manures (Tambone *et al.*, 2010; Alburquerque *et al.*, 2012; Möller and Müller, 2012; Wentzel *et al.*, 2015). Compared to synthetic mineral fertiliser, digestates have lower total N values but are comparable to mineral N in ammonium supply, indicating an ability to supply plant-available nitrogen (Möller and Müller, 2012). Beyond increased nitrogen content, digestate also has higher phosphorus and potassium levels compared to composts (Tambone *et al.*, 2010). There is evidence that biogas digestate has the ability to match or outdo synthetic fertiliser yields in biomass crop (Gissén *et al.*, 2014) and grassland production (Walsh *et al.*, 2012). The high plant-available nutrient content of AD by-products make them a promising fertiliser source for organic and low-input management.

Biogas digestate can be available as both a solid and liquid-form fertiliser and can be applied to match plant nitrogen demand (Makádi *et al.*, 2012). This provides a high plant-available N resource for organic production and biogas digestate has been used to improve winter wheat yields in a stockless organic production system (Stinner *et al.*, 2008) and overall yields in a mixed organic system when incorporated into the soil (Möller *et al.*, 2008). While the potential for biogas digestate within organic systems is lauded by many, there are concerns and constraints. AD digestate has a much lower C:N ratio than composts, which can limit short-term nitrogen availability (Alburquerque *et al.*, 2012; Möller and Müller, 2012) and digestates have lower organic matter content (Tambone *et al.*, 2010; Alburquerque *et al.*, 2012; Möller and Müller, 2012; Wentzel *et al.*, 2015), leading to concerns about digestate reducing soil microbial activity (Wentzel *et al.*, 2015). Additionally, the application of biogas digestate in organic farming systems is currently highly regulated and growers wishing to apply digestate need to follow the prescriptions of their certifying body and comply with EU regulations (EU Commission Regulation No. 142/2011). Despite these drawbacks, if biogas digestate can be used in efficient quantities within regulatory standards, the fertiliser has a clear role in the future of sustainable agriculture as both a source of energy and waste recycling.

2.4 FARMER PARTICIPATORY RESEARCH

Efforts to improve sustainable agriculture production toward future global food security include research support for trialling new technology and alternatives to industrial production systems. Farmer participatory research will certainly contribute to the development of sustainable management, to evaluate the practical efficacy of recommended practices.

On-farm experimentation has always been a component of agricultural production, but agricultural researchers have not always centralised farmers, even in on-farm research. Though farmers observe and experiment with a unique set of conditions each time they grow a crop, on-farm projects are often labelled as non-scientific ‘demonstrations’ (Cook *et al.*, 2013). Chambers et al. (1989) emphasised a ‘farmer first’ approach that shifted the focus to farmer participation as a means of developing innovative on-farm research. From this perspective, a participatory approach encourages researchers to understand farmers’ subjective goals and constraints while acknowledging their experiential technical knowledge (Farrington and Martin, 1988). The specific applications of 'farmer first' experimentation may vary, but the essential definition of farmer participatory research is a systematic collaboration between farmers and researchers to address issues in agriculture with the goal of increasing research impacts (Hellin *et al.*, 2008; Neef and Neubert, 2011). Farmer participatory trials are often used for cultivar evaluation across multiple sites (Yan *et al.*, 2002; Llewellyn, 2007) and the development of precision agriculture technologies (especially yield monitors) have increased on-farm trials of nutrient management practices (Griffin *et al.*, 2014; Kindred and Sylvester-Bradley, 2014; Sylvester-Bradley *et al.*, 2017; Marchant *et al.*, 2019). Collaborative research will be a key component of developing sustainable agricultural systems to meet the demands of population growth and on-farm participatory trials will provide valuable opportunities for farmers and researchers to complement each other (Cook *et al.*, 2013).

2.4.1 BENEFITS OF FARMER PARTICIPATORY RESEARCH

A primary advantage of farmer participatory research is the opportunity to evaluate agricultural practices under the conditions in which they are ultimately intended to be used (Lockeretz, 1987). Cultivars, inputs and management strategies that are effective at experimental field sites under controlled conditions may react differently on farm. Participatory trials allow for analysis under realistic farm conditions (Lockeretz, 1987), which includes at a relevant scale for commercial production (Rzewnicki *et al.*, 1988; Sylvester-Bradley *et al.*, 2017) and with awareness of economic feasibility (Rzewnicki *et al.*, 1988). Farmers often question broad commercial-scale recommendations from small-plot experiments, as the specific conditions of a single-location experiment may not be relevant to their farm in the face of local confounding factors (Pannell *et al.*, 2006; Marchant *et al.*, 2019). The 'real-world' relevance of farmer participatory research also provides insight into site-specific effects, which allow researchers to evaluate techniques outside of an experimental field (Lockeretz, 1987) and help farmers improve their understanding of practices that best suit their farm conditions (ADAS, 2018). Including farmers in defining research objectives may also draw attention to methods or systems already in place that have not been formally studied (Lockeretz, 1987), encouraging researchers to consider practical agronomic management in experimental design.

Farmer participatory research also facilitates networking and collaboration between and among farmers and researchers. Trials focused on a particular aspect of crop production bring interested stakeholders together to exchange ideas and experiences and provides opportunities for in-person networking (Rzewnicki, 1991; Ingram, 2008; Sylvester-Bradley *et al.*, 2017;

ADAS, 2018). Collaborating with researchers through participatory trials can improve farmer perceptions of research-derived agronomic practices (Rzewnicki, 1991) and viewing farmers as innovators within a project improves research quality and impacts (Ingram, 2008; MacMillan and Benton, 2014). Recent agronomic projects encourage farmers to take ownership of their own crop trials by using precision cropping technologies and related electronic data recording tools to assemble comprehensive multi-field and farm data, which is increasingly available through open source frameworks (Sylvester-Bradley *et al.*, 2017; ADAS, 2018). This type of participatory research encourages broader knowledge exchange between growers and researchers, as new practices and products can be widely disseminated through online resources.

Even though many farmers 'unofficially' innovate and experiment on their farms all the time, self-directed experimentation is often difficult in the face of uncertainty. Experimenting within a larger research trial allows for farmers to evaluate new practices (Franzen *et al.*, 2004; Lawes and Bramley, 2012; ADAS, 2018) while offsetting the risks of adopting new techniques (Ashby, 1986). Allowing participants to trial products and strategies within a research project also encourages technology transfer (Rzewnicki, 1991; Witcombe, 1999; Franzen *et al.*, 2004; ADAS, 2018). Farmers are likely to adopt new practices through participation in on-farm trials, especially after experiencing a productivity increase or other agronomic benefit (Witcombe, 1999). The combination of trialling methods in a real-world context and collaborative nature of participatory-research encourages uptake of experimental techniques, increasing the overall impact of on farm trials.

2.4.2 BARRIERS TO FARMER PARTICPATORY RESEARCH

While farmer participatory trials have become key resources for agronomic research, limitations inhibit widespread use of on-farm trials. The primary hindrances likely differ based on perspective—farmers are wary of the time and resource consuming nature of experimental trials while researchers have concerns over their ability to control experimental conditions.

Farmer participatory trials require diversion of farmer time and resources from typical production, which results in additional costs (Griffin *et al.*, 2014). In order to produce publishable research from participatory trial studies, trial monitoring, record-keeping and data collection need to meet scientific research standards. For participant farmers, this means that much more time and effort is required than typical production operations (Lockeretz, 1987; Pannell *et al.*, 2006; Griffin *et al.*, 2008; Griffin *et al.*, 2014; ADAS, 2018; Marchant *et al.*, 2019). Yield data is of particular interest in farmer-trials, yet harvest is a very disruptive time, as farmers rush to complete harvest within a restricted time-frame and farmers are generally concerned about reduced yields and/or poorer gross margins based on experimental conditions (Griffin *et al.*, 2014). Ideally, growers will be compensated for their contribution, but one of the main barriers to widespread farmer participatory research, including in the UK, is a lack of funding (Edwards-Jones, 2001). Without appropriate remuneration, many farmers cannot feasibly participate in the research process (Llewellyn, 2007). Especially if participatory trials aim to drive farmer progress, a balance needs to be struck to allow for reliable and robust data collection and management with minimal disruption to usual farm activities (Marchant *et al.*, 2019). The time and effort demands do not always fall solely on farmers. Especially if a trial has a complex design with demanding assessments, researchers may take on more responsibility for data collection, which becomes much more difficult when sites are based away from the researcher's home institution (Lockeretz, 1987).

The potential complexity of managing multi-site participatory trials is also a concern for experimental design and management. If on-farm data collection is intended to primarily be the responsibility of the farmer, simpler designs are preferred, both by farmers (Hicks *et al.*, 1997; Griffin *et al.*, 2008) and by researchers, because this risks incomplete and inaccurate record-keeping (Lockeretz, 1987). While simpler trial designs are more accessible to farmers, they may lack the accuracy and robustness to draw accurate and replicable conclusions (Lawes and Bramley, 2012; ADAS, 2018). This also highlights a key conflict between researcher and farmer expectations. Researchers are often focused on creating a robust experiment to assign statistical significance while farmers don't recognise this benchmark and are primarily concerned with profitability (Whelan *et al.*, 2012; Marchant *et al.*, 2019). A successful farmer participatory trial should benefit both farmers and researchers, striking a balance between experimental complexity and practical feasibility.

CHAPTER 3. SPELT

Evaluating organic fertilisers and their impact on yield and quality of spelt

3.1 INTRODUCTION

Spelt (*Triticum spelta*) is an ancient wheat species, commonly referred to as a 'hulled' wheat, due to the tough glume which surrounds the seed. The minor grain fell out of favour with the advent of synthetic fertilisers as its inconsistent yield could not compete with breeding programmes for free-threshing wheats (Stallknecht *et al.*, 1996; Longin *et al.*, 2015), but the same characteristics that limited its development have led to renewed interest in spelt for sustainable agriculture.

Spelt has historical ties to the Middle East and Northern Europe and has been cultivated for millennia, serving as a key crop across a wide range of cultures and ancient societies (Stallknecht *et al.*, 1996; Bavec and Bavec, 2006; Arzani and Ashraf, 2017). Spelt responds to low-input fertility and its characteristic hull protects the grain from pollutants, insects and disease, retains nutrients in the kernel and enhances seed germination (Bonafaccia *et al.*, 2000; Bavec and Bavec, 2006; Konvalina *et al.*, 2010; Lacko-Bartošová *et al.*, 2010; Pospišil *et al.*, 2011). Due to these characteristics, spelt is widely considered a crop best suited for organic and low-input production systems.

Despite achieving lower yields and requiring additional post-harvest processing compared to modern wheats, demand for spelt from consumers, bakers and farmers has grown considerably. This is due partially to the crop's ability to grow in harsh/varied climatic conditions (Ranhotra *et al.*, 1995; Bonafaccia *et al.*, 2000; Burgos *et al.*, 2001), which is increasingly valued in the face of climate change and through growing consumer interest in wholegrain foods.

Relative to common wheat, spelt is easily digestible (Bonafaccia *et al.*, 2000), to the point that individuals with certain wheat allergies can consume spelt without consequence (Stallknecht *et al.*, 1996). Spelt varieties have also been shown to have higher protein and mineral content compared to modern wheats (Stallknecht *et al.*, 1996; Pospišil *et al.*, 2011; Arzani and Ashraf, 2017), which continues to fuel interest in developing spelt-based products.

This chapter evaluates the yield and quality performance of European spelt varieties (both landraces and common cultivars) grown with low-input fertiliser types and rates in a UK-based field trial.

3.2 MATERIALS AND METHODS

3.2.1 EXPERIMENTAL DESIGN

The effects of fertiliser type and variety on crop yield and quality were assessed in spelt and rye in a two-year experimental field trial at Nafferton Farm. Crop health assessments, including disease severity and SPAD (Soil-Plant Analyses Development) readings, occurred throughout the growing season in both years. Grain yield and yield components were determined at harvest, including total biomass, combine yield, thousand grain weight (TGW) and harvest index (HI). Harvested grain was further analysed for grain quality parameters, including Hagberg Falling Number (HFN), specific weight, protein content and nutritional profile.

3.2.1.1 SITE DESCRIPTION

The field trials were located at Nafferton Farm in North East England (54:59:26.3 N; 1:54:37.4 W) and carried out over two consecutive growing seasons (2014-15 and 2015-16 respectively, referred to throughout as 2015 and 2016). Existing long-term, multi-factorial field experiments were utilised to identify interactions between fertiliser rate, fertiliser input types, variety choice and trial year. The soil in the plots is a slowly permeable clay loam of the Brickfield/Dunkeswick soil series with an average pH of 6.75, P-index of 0, K-index of 1 and Mg-index of 3 at the start of the experiment (Table 3.2.1). Total available nitrogen in the soil of experimental plots was higher in 2016 (21.0-31.6 mg/kg at 0-30cm; 8.5-10.4 mg/kg at 30-60cm) than 2015 (10.8-13.5 mg/kg at 0-30cm; 6.8-8.2 mg/kg at 30-60cm) (Table 3.2.2). Weather data was recorded throughout the experimental period by an automated station situated 500m from the field trials at Nafferton Farm (Table A.1., Appendix A).

3.2.1.2 EXPERIMENTAL LAYOUT

The experimental design was planned as a component of the EU 7th Framework Programme HealthyMinorCereals (HMC) project. The trial plots were in a 4.8ha field divided into four replicate blocks (Figure 3.2.1). The blocks each contained ten 24m x 24m plots, of which five plots within each block were used for the spelt and rye trials. In each trial year, two and a half of the plots within each block were sown in cereals while the other two and a half plots were in a grass/white clover ley to allow for a rotation between trial years. Fertiliser rate was the main-plot (24m x 24m), variety was the sub-plot (24m x 3m) and N fertiliser type was the sub-sub-plot (24m x 6m) so that each individual sub-sub-plot was 3m x 6m and included a specific fertiliser rate, variety and fertiliser type. (Figure 3.2.2 & Figure 3.2.3).

Table 3.2.1 Soil phosphorus, potassium and magnesium index in 2015 and 2016.

Year	Fertiliser Rate	Soil pH	P Index	P mg/l	K Index	K mg/l	Mg Index	Mg mg/l
2015	HIGH	6.8 ± 0.11	0	8.6 ± 0.74	1	85.0 ± 5.12	3	155 ± 7.4
	ZERO	6.7 ± 0.12	0	8.1 ± 0.33	1	82.5 ± 3.59	3	151 ± 6.1
2016	HIGH	6.6 ± 0.03	0	7.3 ± 0.76	1	77.0 ± 7.18	3	162 ± 5.64
	ZERO	6.5 ± 0.10	0	6.8 ± 0.78	1	74.5 ± 2.18	3	166 ± 2.92

Soil was analysed in October from plots designated for either high rate (100 kgN/ha) or zero rate fertiliser applications to account for any difference within the experimental area with soil samples collected prior to any fertiliser application. Samples were analysed by NRM Laboratories (Bracknell, Berkshire).

Table 3.2.2. Soil dry matter (DM), nitrate-nitrogen (NO_3 – N), ammonium-nitrogen (NH4 - N) and total nitrogen content measured at two depths in 2015 and 2016.

Year	Fertiliser type	Fertiliser Rate	Soil DM %	NO_3 - N mg/kg	NH^4 - N mg/kg	Total available N kgN/ha
			Sampled at 0-30 cm			
2015	FYM	HIGH	79.2 ± 0.21	2.3 ± 0.24	1.2 ± 0.11	13.0 ± 1.20
	PRE MN	NA	77.7 ± 0.83	2.3 ± 0.24	1.3 ± 0.26	13.5 ± 1.75
	ZERO	ZERO	81.4 ± 1.46	1.7 ± 0.38	1.1 ± 0.21	10.8 ± 2.13
2016	FYM	HIGH	79.3 ± 0.90	4.1 ± 0.64	1.5 ± 0.29	21.0 ± 2.06
	PRE MN	NA	79.2 ± 0.23	4.8 ± 0.60	1.4 ± 0.23	23.3 ± 2.83
	ZERO	ZERO	79.8 ± 0.35	6.8 ± 1.08	1.6 ± 0.29	31.6 ± 4.47
			Sampled at 30-60 cm			
2015	FYM	HIGH	83.4 ± 0.32	1.0 ± 0.19	0.8 ± 0.03	6.8 ± 0.74
	PRE MN	NA	83.7 ± 0.45	1.3 ± 0.10	0.9 ± 0.04	8.2 ± 0.34
	ZERO	ZERO	83.6 ± 0.43	0.9 ± 0.23	1.0 ± 0.13	7.3 ± 0.62
2016	FYM	HIGH	84.2 ± 0.27	1.5 ± 0.43	0.7 ± 0.08	8.5 ± 1.84
	PRE MN	NA	83.3 ± 0.44	1.9 ± 0.25	0.9 ± 0.22	10.4 ± 0.55
	ZERO	ZERO	83.3 ± 0.37	1.8 ± 0.18	0.8 ± 0.13	9.7 ± 0.24

Soil was analysed from plots designated as a zero control and high rate (100 kgN/ha) FYM compost or Mineral N applications to account for any difference within the experimental area, with samples collected in March after FYM application but prior to Mineral N application. Samples were analysed by NRM Laboratories (Bracknell, Berkshire).

S1	Ob. Rotkorn	Low N: 50kgN/ha
S2	ZOR	High N: 100kgN/ha
S3	Rubiota	Cattle Slurry
S4	Filderstolz	Composted FYM
R1	Elvi	Biogas Digestate
R2	Elias	Mineral N
R3	Schlaegler	Green Waste
R4	Dank. Amber	Zero Input

Figure 3.2.1. Full field trial design of the spelt and rye trials, including four replicate blocks. Five of the ten square plots (24m x 24m) within each block were designated for the spelt and rye trials, while the remaining five were used for completely separate experiments. The order of fertiliser types and varieties was randomized within the layout in each replicate. Grass/clover leys were included to allow rotation between trial years. Green waste compost was applied to plots as part of a separate trial—it is included in the experimental design figure to show the full trial layout but further results and discussion from these plots are not included.

Figure 3.2.2. The spelt and rye trials as viewed from one end of a replicate block in June 2016. The four varieties of spelt are on the left; the four rye varieties are on the right.

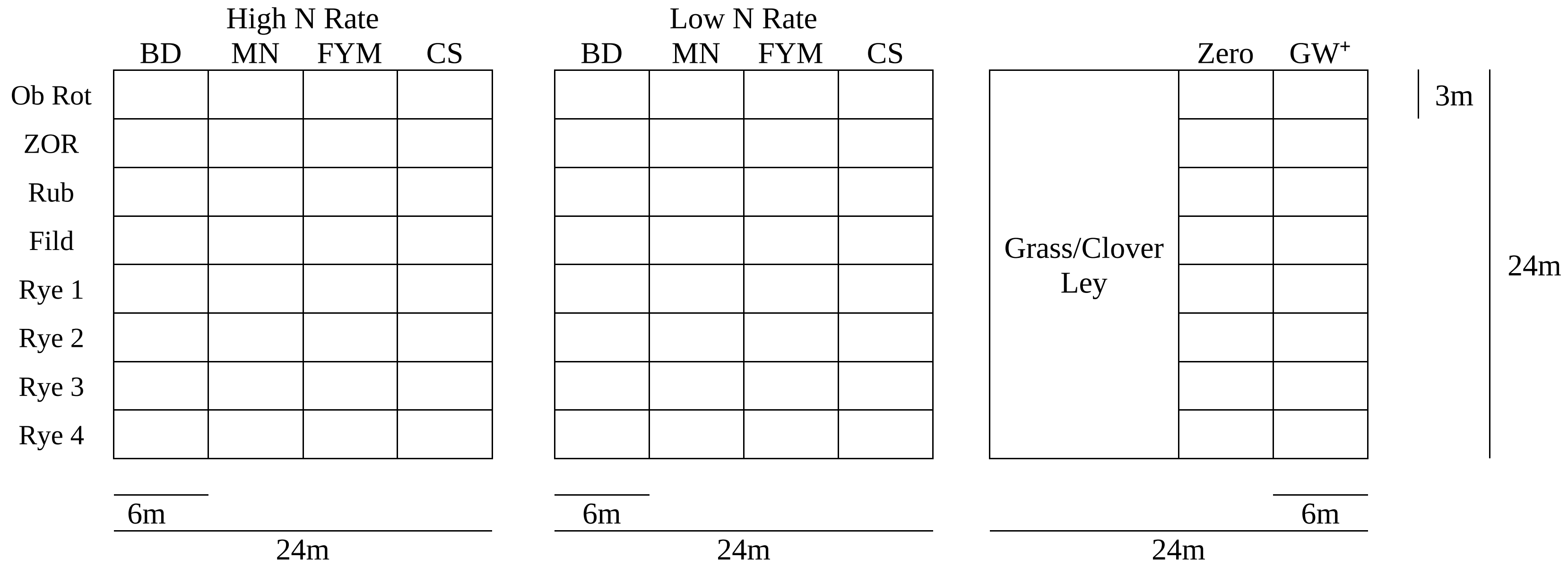

Figure 3.2.3. Field trial design for the spelt trials. The layout represents one replicate of two and a half 24m x 24m main plots. Varieties were sown length-wise in 24m x 3m sub-plots across the full main plots and 12m x 3m sub plots across the half main plot. Fertiliser inputs were applied across the varieties at a perpendicular angle in 24m x 6m strips and fertiliser rates were applied to main plots (24m x 24m) as high rate (100kgN/ha), low rate (50kgN/ha) and zero input (0kgN/ha). The order of fertiliser types and varieties was randomized within the layout in each replicate (zero-input treatments were always alongside grass/clover). $^{+}$Green waste compost (GW) was applied to plots as part of a separate trial—it is included in the experimental design figure to show the full trial layout but further results and discussion from these plots are not included.

3.2.1.3 AGRONOMIC MANAGEMENT

The factorial experiments included four varieties of spelt: Oberkulmer Rotkorn (Ob Rot), Zuercher Oberlaender Rotkorn (ZOR), Rubiota (Rub) and Filderstolz (Fild). Rubiota is a modern Czech variety. The Ob Rot and ZOR varieties were sourced from Sativa Rheinau (Rheinau, Switzerland). Oberkulmer is an old Swiss landrace and ZOR is a modern variety first registered in 2012 and bred by the Peter Kunz breeding group (Getreidezüchtung Peter Kunz). Filderstolz is a modern semi-dwarf German variety developed by the University of Hohenheim (Stuttgart, Germany) to have *Rht* dwarfing genes through a cross with the wheat variety Maris Huntsman. Variety selection was determined by partners within the HealthyMinorCreals project consortium. All varieties were sown on 1 October 2014 in the first year and on 5 October 2015 in the second year of the trial (Table 3.2.3). All varieties were sown at 350 hulled seeds/m^2 for the 2015 trial and at 250 hulled seeds /m^2 in the 2016 trial with rates calculated based on variety thousand grain weight (Table 3.2.4).

The fertiliser regimes involved two fertiliser rates: 100 kg total N/ha (High) and 50 kg total N/ha (Low) and 4 N fertiliser input types: synthetic mineral nitrogen (MN), farm yard manure compost (FYM), cattle slurry (CS) and biogas digestate from an anaerobic digester (BD) together with a zero-input control[1]. FYM and CS were sourced from Nafferton Farm, BD was supplied by DJ & SJ Enderby Recycling (Hexham, Northumberland) and MN was Nitram® Ammonium Nitrate (34.5%N). In both years, FYM was applied in late September, prior to drilling and the remaining fertiliser types (MN, CS and BD) were applied to the growing crops on 16 April in 2015 and 11 May in 2016 (Table 3.2.3). Fertiliser application amounts were calculated based on total N in each fertiliser type to use rates equivalent to 100 and 50 kgN/ha for each fertiliser (Table 3.2.5).

Prior to this project, the experimental field was in a grass/clover ley for two years. To prevent confounding effects of mechanical weed control on nitrogen availability, the plots were sprayed with herbicides: Cleancrop Gallifrey (fluroxypyr; 0.6L/ha) on 17 April 2015 and with Cleancrop Gallifrey (0.35L/ha) and Isomec Ultra (dichloroprop-p; 1.5L/ha) on 11 April 2016 (Table 3.2.3). No fungicide treatments were applied to control disease in either trial year.

[1] A fifth fertiliser input type, green waste compost (GW) was also applied to plots as part of a separate trial. The GW plot is included in the experimental design figure to show the full trial layout but further results and discussion from these plots are not included.

Table 3.2.3. Crop management details for spelt trials in 2015 and 2016.

	2015	**2016**
Previous crop	2 years grass/clover	3 years grass/clover
Sowing date	1 October 2014	5 October 2015
Biomass harvest date	1-3 September 2015	2-5 September 2016
Combine harvest date	8-9 September 2015	15-18 September 2016
Herbicide Application Dates		
CleanCrop Gallifrey (*fluroxypyr*)	17 April 2015 (0.6 L/ha)	11 April 2016 (0.35 L/ha)
Isomec Ultra (*dichloroprop-p*)		11 April 2016 (1.5 L/ha)
Fertiliser Application Dates		
Biogas Digestate	16 April 2015	11 May 2016
Cattle Slurry	16 April 2015	11 May 2016
FYM Compost	29 September 2014	22 September 2015
Mineral N	17 April 2015	10 May 2016

Table 3.2.4. Seeding rates (kg/ha) for each spelt variety sown in 2015 and 2016.

	2015	**2016**
Oberkulmer Rotkorn	368	315
ZOR+	403	300
Rubiota	277	320
Filderstolz	410	293

All varieties were drilled at 350 hulled seeds/m^2 in 2015 and 250 hulled seeds/m^2 in 2016.
+ZOR in 2015 was sown at 300 seeds/m^2 due to inadequate seed supply

Table 3.2.5. Nitrogen content (% dry matter) of each fertiliser type used in 2015 and 2016.

	2015	**2016**
Biogas Digestate	10.00	6.23
Cattle Slurry	5.56	3.69
FYM Compost	3.05	3.63
Mineral N	34.5	34.5

3.2.2 EXPERIMENTAL ASSESSMENTS

3.2.2.1 GROWING SEASON ASSESSMENTS

A single germination count took place in early November of both trial years. Spelt leaves were monitored for the key foliar diseases powdery mildew (*Blumeria graminis* f. sp. *tritici*), septoria leaf blotch (*Septoria tritici*) and yellow stripe rust (*Puccinia striiformis*) at multiple growth stages (GS). Beginning with first signs of disease at GS30/31[2], disease assessments occurred every two

[2] Disease assessments using AUDPC typically begin at GS37, with flag leaf emergence. The spelt began to show signs of disease prior to GS37 and flag leaves senesced much earlier than the rye, therefore disease assessments on spelt began at GS30/GS31. Adjustments to the AUDPC calculation were made for this first date to reflect that the first leaf was not the flag leaf for this assessment.

weeks through to maturity. Within each trial plot, the top four leaves of ten randomly selected plants were examined for presence and severity of disease. At GS82/83, crops were assessed for fusarium head blight (*F. graminearum*), ergot (*Claviceps purpurea*) and *P. striiformis* in the ear by selecting ten tillers at random within each plot and examining ears for disease presence and severity. Leaves and ears were scored in the same manner, given a rating of 0 (no disease present), 1%, 5%, 10%, 25%, 50%, 75% or senesced. Scores from each sample were averaged to provide a measurement for each plot, which was used with assessment date to collate an Area Under the Disease Progress Curve (AUDPC) (Jeger, 2004).

Indirect leaf chlorophyll concentration measurements were taken with a SPAD hand-held chlorophyll meter (SPAD 502 Plus). Beginning the week after disease assessments commenced (GS39 in 2015, GS33 in 2016), SPAD readings were taken on the flag leaf of ten randomly selected plants from each plot every two weeks in conjunction with disease assessments up to the end of flowering (GS68). Chlorophyll content is included as an indication of leaf N content due to the linear relationship between leaf nitrogen and chlorophyll content in plants (Evans, 1989). Measuring chlorophyll with a SPAD meter comes with caveats, as chlorophyll content is not uniformetly distributed in plant leaves, which contributes to variation in SPAD meter readings and actual chlorophyll concentration (Parry et al., 2014). With this limitation in mind, SPAD readings were not considered absolute measures of leaf chlorophyll or N content but are included to demonstrate relative differences between N fertilser treatments.

Plant height measurements were taken at anthesis (GS68) and during biomass harvest by selecting three plants at random within each plot and measuring from ground level to the top of the ear. The three scores from each sample were averaged to provide a plant height measurement for each plot.

3.2.2.2 **GRAIN YIELD ASSESSMENTS**

Prior to harvest, biomass samples were removed from each plot to assess total biomass, harvest index, moisture content and additional yield components. Plants from 4 x 0.5m rows were counted and removed from each plot. In 2015, spelt biomass was collected from 1-3 September; in 2016, spelt biomass was collected from 2-5 September (Table 3.2.3). Crops were harvested with a plot combine (Claas Dominator 38; Class UK Ltd, Bury St Edmunds UK) and a sample of grain (about 1 kg) was taken and used for grain quality assessments. In 2015, harvest occurred on 8-9 September; in 2016 crops were harvested 15-18 September (Table 3.2.3). Harvest index was calculated as the ratio between grain yield and total crop biomass (biomass harvest and processing described in next section).

3.2.2.3 YIELD COMPONENT ASSESSMENTS

Biomass harvest samples were individually processed for each plot. Tillers and ears were counted, separated and weighed. Sub-samples of straw (max 50g) and ears (max 150g) were weighed and dried (80°C for 2 days or 70°C for 3 days) for each sample, then used to calculate moisture content and retained for further analysis. After harvest, 200g of combined grain from each sample were weighed out and oven dried (40°C for four days) to measure moisture content.

Combined grain and biomass ear samples were dried, cleaned and threshed at Nafferton farm using a seed cleaner and thresher. Spelt is combined with a hull and was cleaned by threshing each sample 5 times to remove the husk in 2015. In 2016, dried spelt samples were de-hulled using a small de-huller at Gilchesters Organics (Stamfordham, Northumberland).

Clean, dried and threshed combine grain and biomass ear samples were run through an electronic seed counter to measure thousand grain weight. Grain from biomass ear samples were weighed to calculate seed weight for additional parameters. Grain number was calculated based on grain yield and average grain weight.

3.2.2.4 GRAIN MILLING QUALITY ASSESSMENTS

Sub samples of 500 grams from each sample were taken to Coastal Grains Ltd (Belford, Northumberland) to measure Hagberg Falling Number, specific weight and grain size screenings. HFN was measured on all samples except those not treated with fertiliser (No Input) while all samples were processed for specific weight, percent moisture and grain size.

Spelt samples were analysed for specific weight in a FOSS Infratec™1241 Analyzer. HFN was analysed in a Perten Falling Number 1310 Analyser using flour samples milled in a Perten LabMill 3100 and following the analytical method described by Perten Instruments (Perten, 2016). A Pfeuffer Sortimat was used to screen 100g of each sample into three sizes (2.2mm, 2.5mm and 2.8mm).

3.2.2.5 GRAIN NUTRIENT QUALITY ASSESSMENTS

Analyses of nutritional components of grain samples was completed by Sabanci University in Turkey, including concentrations of nitrogen, total phenolic content (TPC), micronutrients (Ca, Cu, Fe, Mn, Zn) and macronutrients (K, Mg, P, S). Samples were analysed for total N by Dumas combustion (Elementar Vario Macro Cube, Elementar, DE). Grain N content was multiplied by 5.7 to estimate grain protein concentration (AOAC International, 2016). Additional grain macro-micro nutrient concentrations were determined by subjecting samples to nitric acid (HNO_3) digestion in a closed-vessel microwave reaction system (MarsExpress; CEM Corp., Matthews, NC, USA) and analysing with an inductively coupled argon plasma optical emission spectrometer equipped with a charge coupled device detector (Vista-Pro Axial; Varian Pty Ltd, Mulgrave, Australia).

3.2.3 STATISTICAL ANALYSIS

Data analysis was completed using the Linear and Nonlinear Mixed Effects Models (nlme) and Simultaneous Inference in General Parametric Models (multcomp) packages in the statistical software R (R Core Team, 2018).

ANOVAs from linear mixed-effects models from 'nlme' were used to assess the effects of year, fertiliser rate, fertiliser type and genotype on measured parameters. The hierarchical split-split-split-plot design was designated in the random error structures of the model as: block/year/fertiliser rate/fertiliser type. The control plot (No Input) measurements were not included in ANOVAs but means and standard errors are presented in the results tables.

If significant differences (p-value <0.05) occurred between fertiliser types, varieties and/or interactions between factors, general linear hypothesis tests (Tukey contrasts) were performed using the 'glht' function in the 'multcomp' package. As described for the linear mixed-effects models, the split-split-split-plot design was reflected in the random error structures.

The relationship between weather (air temperature, radiation, precipitation and relative humidity), fertiliser treatment (type and rate), variety and grain yield and quality parameters was assessed on data from both years using redundancy analysis (RDA), with trial blocks as co-variables. The RDA was carried out using the CANOCO package (ter Braak and Šmilauer, 2012).

3.3 RESULTS

3.3.1 GRAIN HARVEST

3.3.1.1 GRAIN YIELD

Significant main effects of year were detected for spelt grain yield ($p = 0.032$); grain yield was significantly higher in 2015 than in 2016 (Table 3.3.1). Highly significant main effects of fertiliser type and variety ($p < 0.001$) were detected for grain yield; biogas digestate produced significantly higher yields than all other fertiliser types and Oberkulmer Rotkorn was the highest yielding variety (Table 3.3.1).

3.3.1.2 PLANT HEIGHT

Significant main effects of year were detected for spelt plant height ($p = 0.010$); plant height was significantly higher in 2015 than in 2016 (Table 3.3.1). Highly significant main effects of fertiliser type and variety ($p < 0.001$) were detected for plant height; biogas digestate produced taller plants but differences in plant height were not significantly different based on post-hoc analysis; Oberkulmer Rotkorn and Rubiota were the tallest and Filderstolz was the shortest variety (Table 3.3.1).

3.3.1.3 HARVEST INDEX

Highly significant main effects of variety ($p < 0.001$) were detected for harvest index; Filderstolz had a significantly higher HI to all other varieties (Table 3.3.1).

Significant interaction effects of fertiliser rate and type were detected for harvest index ($p = 0.017$) (Table 3.3.1); mineral N had significantly higher HI at low rate fertility (50kg N/ha) compared to high rate (100kg N/ha) applications (Table 3.3.2). The interaction between year and variety was highly significant for HI ($p < 0.001$) (Table 3.3.1); the variety Filderstolz had a significantly higher harvest index in 2016 compared to 2015 while all other varieties had a lower HI in 2016 (Table 3.3.3).

Table 3.3.1. Main effect means, ±SE and p-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on spelt yield, plant height and harvest index (HI).

	Grain Yield (t/ha)	**Plant Height (cm)**	**HI (%)**
Year			
2015	3.60 ± 0.062	123.3 ± 1.83	31.3 ± 0.37
2016	2.86 ± 0.071	112.2 ± 1.44	31.0 ± 0.78
Fertiliser Rate			
0kg N/ha	2.90 ± 0.143	114.5 ± 3.49	34.5 ± 1.48
50kg N/ha	3.18 ± 0.072	117.2 ± 1.83	31.7 ± 0.55
100kg N/ha	3.36 ± 0.083	119.2 ± 1.82	29.8 ± 0.69
Fertiliser Type			
BD	3.64 ± 0.120 a	121.2 ± 2.56 a	30.2 ± 0.82
CS	3.29 ± 0.112 b	115.4 ± 2.41 a	32.2 ± 0.84
FYM	3.08 ± 0.087 b	116.5 ± 2.56 a	30.6 ± 0.75
M	3.08 ± 0.105 b	119.6 ± 2.77 a	29.9 ± 1.08
Variety			
Fild	2.60 ± 0.076 c	93.6 ± 1.00 c	35.7 ± 1.01 a
Ob Rot	3.74 ± 0.091 a	135.0 ± 1.17 a	28.8 ± 0.65 c
Rub	3.32 ± 0.107 b	135.0 ± 1.48 a	27.7 ± 0.70 c
ZOR	3.26 ± 0.093 b	107.5 ± 1.01 b	32.4 ± 0.72 b
ANOVA *p*-values			
Main Effects			
yr	**0.032**	**0.010**	NS
fr	NS	NS	NS
ft	**<0.001**	**<0.001**	NS
var	**<0.001**	**<0.001**	**<0.001**
Interactions			
yr:fr	NS	NS	NS
yr:ft	NS	**0.008**	NS
fr:ft	NS	NS	**0.017**
yr:var	NS	**<0.001**	**<0.001**
fr:var	NS	NS	NS
ft:var	NS	NS	NS
yr:fr:ft	**0.048**	NS	**0.027**
yr:fr:var	NS	**0.021**	NS
yr:ft:var	NS	NS	NS
fr:ft:var	NS	NS	NS
yr:fr:ft:var	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVA.

Table 3.3.2. Interaction means ±SE for the effects of trial year and fertiliser type on spelt harvest index.

	Harvest Index (%)			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
50kg N/ha	30.0 ± 1.19 Aa	32.3 ± 0.89 Aa	31.7 ± 1.07 Aa	32.7 ± 1.20 Aa
100kg N/ha	30.4 ± 1.16 Aa	32.2 ± 1.45 Aa	29.5 ± 1.02 Aab	27.0 ± 1.67 Bb

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test $p < 0.05$).

Table 3.3.3. Interaction means ±SE for the effects of trial year and variety on spelt harvest index.

	Harvest Index (%)			
	Filderstolz	**Ob Rotkorn**	**Rubiota**	**ZOR**
2015	31.3 ± 0.94 Ba	30.9 ± 0.40 Aa	29.7 ± 0.94 Aa	31.9 ± 0.63 Aa
2016	39.3 ± 1.72 Aa	25.9 ± 1.12 Bc	25.4 ± 1.02 Bc	31.5 ± 1.08 Ab

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test $p < 0.05$).

3.3.2 YIELD COMPONENTS

Significant main effects of year were detected for spelt ears/m^2 ($p = 0.006$), grains/m^2 ($p = 0.009$) and thousand grain weight ($p = 0.001$), which were all significantly higher in 2015 than 2016 (Table 3.3.4). Fertiliser type main effects were significant for ears/m^2 ($p = 0.009$), grains/m^2 ($p = 0.008$) and grains/ear ($p = 0.022$); mineral N had the lowest ears and grains/m^2 and biogas digestate had the highest grains/ear (Table 3.3.4). Highly significant main effects of variety ($p < 0.001$) were detected for spelt ears/m^2, grains/m^2 and TGW and significant main effects of variety were detected for grains/ear ($p = 0.028$); Oberkulmer Rotkorn TGW was significantly higher while ZOR TGW was significantly lower than all other varieties (Table 3.3.4).

Table 3.3.4. Main effect means, ±SE and p-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on spelt ears/m^2, grains/m^2, grains/ear and thousand grain weight (TGW).

	Ears/m^2	**Grains/m^2**	**Grains/Ear**	**TGW (g)**
Year				
2015	351 ± 7.5	5110 ± 151.2	14.5 ± 0.29	49.3 ± 0.41
2016	238 ± 6.9	3405 ± 114.7	14.6 ± 0.33	44.7 ± 0.19
Fertiliser Rate				
0kg N/ha	280 ± 16.2	3711 ± 282.5	13.5 ± 0.71	47.3 ± 0.66
50kg N/ha	303 ± 8.6	4353 ± 145.4	14.5 ± 0.30	47.3 ± 0.40
100kg N/ha	289 ± 9.9	4300 ± 178.4	14.8 ± 0.34	46.6 ± 0.41
Fertiliser Type				
BD	299 ± 12.4 a	4666 ± 250.1 a	15.5 ± 0.47 a	47.1 ± 0.57
CS	308 ± 12.9 a	4533 ± 206.8 a	14.9 ± 0.43 ab	47.3 ± 0.51
FYM	313 ± 13.1 a	4241 ± 207.8 ab	13.8 ± 0.44 b	46.8 ± 0.57
M	265 ± 13.5 b	3864 ± 243.1 b	14.3 ± 0.46 ab	46.6 ± 0.64
Variety				
Fild	247 ± 10.4 b	3349 ± 138.5 c	14.3 ± 0.55 ab	47.9 ± 0.50 b
Ob Rot	315 ± 13.4 a	4531 ± 195.1 ab	14.5 ± 0.35 ab	49.7 ± 0.61 a
Rub	301 ± 12.3 a	4221 ± 243.8 b	13.7 ± 0.42 b	46.1 ± 0.48 c
ZOR	315 ± 10.9 a	4931 ± 224.2 a	15.5 ± 0.37 a	44.4 ± 0.24 d
ANOVA *p*-values				
Main Effects				
yr	**0.006**	**0.009**	NS	**0.001**
fr	NS	NS	NS	NS
ft	**0.009**	**0.008**	**0.022**	NS
var	**<0.001**	**<0.001**	**0.028**	**<0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	NS	NS	NS	NS
fr:ft	NS	NS	**0.001**	NS
yr:var	NS	**<0.001**	**<0.001**	**<0.001**
fr:var	NS	NS	NS	NS
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	**0.048**	NS
yr:fr:var	NS	NS	NS	NS
yr:ft:var	NS	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

3.3.3 SPAD

Significant main effects of year were detected for SPAD readings at GS39 ($p = 0.007$) and GS59 ($p = 0.013$), which were both significantly higher in 2016 than 2015 (Table 3.3.5). Fertiliser rate main effects were significant at GS30 ($p = 0.006$) and GS39 ($p = 0.002$), with higher SPAD readings in spelt fertilised at the higher rate (100kg N/ha) (Table 3.3.5). At all three growth stages, highly significant main effects of fertiliser type ($p < 0.001$) were detected; biogas digestate had the highest readings at all growth stages, which were not significantly different to mineral N at GS30 and GS39 and to cattle slurry at GS59 (Table 3.3.5). Highly significant main effects of variety ($p < 0.001$) were detected for SPAD readings at all growth stages; Filderstolz had the highest readings at GS30 and GS39 and Oberkulmer Rotkorn readings were not significantly different to Filderstolz at GS39 and were significantly higher than all other varieties at GS59 (Table 3.3.5).

Table 3.3.5. Main effect means, ±SE and p-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on spelt SPAD readings at three growth stages.

	GS30	**GS39**	**GS59**
Year			
2015	34.7 ± 0.29	35.0 ± 0.25	28.4 ± 0.50
2016	36.1 ± 0.25	40.0 ± 0.35	33.1 ± 0.60
Fertiliser Rate			
0kg N/ha	33.2 ± 0.55	34.2 ± 0.55	29.2 ± 1.01
50kg N/ha	34.9 ± 0.27	37.1 ± 0.35	31.0 ± 0.62
100kg N/ha	36.3 ± 0.28	38.8 ± 0.41	30.9 ± 0.65
Fertiliser Type			
BD	37.2 ± 0.37 a	40.0 ± 0.58 a	33.8 ± 0.94 a
CS	34.9 ± 0.41 b	37.0 ± 0.49 b	31.8 ± 0.82 ab
FYM	33.9 ± 0.32 b	34.9 ± 0.39 c	28.4 ± 0.68 c
M	36.6 ± 0.35 a	39.9 ± 0.46 a	30.0 ± 0.99 bc
Variety			
Fild	37.2 ± 0.40 a	38.3 ± 0.62 a	30.4 ± 0.84 c
Ob Rot	35.4 ± 0.35 b	37.7 ± 0.51 ab	36.8 ± 0.44 a
Rub	34.5 ± 0.37 c	36.5 ± 0.49 c	32.9 ± 0.44 b
ZOR	34.3 ± 0.33 c	37.7 ± 0.46 b	23.1 ± 0.53 d
ANOVA *p*-values			
Main Effects			
yr	NS	**0.007**	**0.013**
fr	**0.006**	**0.002**	NS
ft	**<0.001**	**<0.001**	**<0.001**
var	**<0.001**	**<0.001**	**<0.001**
Interactions			
yr:fr	NS	NS	NS
yr:ft	**0.002**	**0.001**	**0.016**
fr:ft	NS	NS	NS
yr:var	NS	**0.010**	**<0.001**
fr:var	NS	NS	NS
ft:var	NS	NS	**<0.001**
yr:fr:ft	NS	NS	NS
yr:fr:var	NS	NS	NS
yr:ft:var	NS	NS	**0.006**
fr:ft:var	NS	NS	NS
yr:fr:ft:var	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Zero treatments were not included in the ANOVAs.

3.3.4 DISEASE SEVERITY

3.3.4.1 YELLOW RUST

Significant main effects of year were detected for yellow stripe rust (*Puccinia striiformis*) AUDPC on L1 ($p = 0.021$), L2 ($p = 0.016$) and L4 ($p = 0.006$); disease severity was significantly higher in

2015 for the first two leaves and was higher in 2016 for L4 (Table 3.3.6). Highly significant main effects of fertiliser type ($p < 0.001$) were detected for yellow rust AUDPC on the first three leaves and significant main effects of fertiliser type were detected on L4 ($p = 0.021$); mineral N had the highest yellow rust severity on all leaves, with no significant difference in disease levels to biogas digestate on L4 (Table 3.3.6). Highly significant main effects of variety ($p < 0.001$) were detected for yellow rust AUDPC on all four leaves; ZOR had the highest yellow rust severity on L1 and Filderstolz had the highest disease levels on the bottom three leaves, with no significant difference in disease severity to Oberkulmer Rotkorn on L4 (Table 3.3.6).

Significant interaction effects of fertiliser rate and type were detected for yellow rust AUDPC on L1 ($p = 0.014$) and L2 ($p = 0.043$) (Table 3.3.6); the high rate (100kg N/ha) of mineral N had significantly higher yellow rust disease severity than all other fertiliser types at both rates (Table 3.3.7).

3.3.4.2 **LEAF BLOTCH**

Significant main effects of year were detected for septoria leaf blotch (*Septoria tritici)* AUDPC on L1 ($p = 0.041$), L2 ($p = 0.005$), L3 ($p = 0.008$) and L4 ($p = 0.006$); septoria disease severity was significantly higher in 2016 than 2015 (Table 3.3.8). Highly significant main effects of variety ($p < 0.001$) were detected for septoria AUDPC on all four leaves; septoria disease severity was significantly higher for the variety ZOR on Leaf 1, ZOR and Filderstolz on Leaf 2, ZOR and Rubiota on Leaf 3 and Oberkulmer Rotkorn on Leaf 4 (Table 3.3.8).

Table 3.3.6. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for yellow stripe rust (*Puccinia striiformis*) on spelt leaves.

	Leaf 1	**Leaf 2**	**Leaf 3**	**Leaf 4**
Year				
2015	229 ± 18.7	482 ± 32.2	397 ± 31.7	104 ± 13.0
2016	38 ± 3.3	186 ± 14.2	553 ± 39.5	493 ± 32.1
Fertiliser Rate				
0kg N/ha	134 ± 28.6	373 ± 69.0	531 ± 90.0	331 ± 77.7
50kg N/ha	125 ± 14.5	304 ± 26.2	446 ± 37.7	275 ± 28.0
100kg N/ha	143 ± 18.8	355 ± 31.1	490 ± 37.8	313 ± 32.1
Fertiliser Type				
BD	102 ± 17.1 b	284 ± 34.7 b	423 ± 47.0 b	305 ± 38.7 ab
CS	97 ± 15.4 b	258 ± 34.7 b	428 ± 49.5 b	254 ± 35.9 b
FYM	126 ± 21.6 b	313 ± 43.2 b	425 ± 57.5 b	243 ± 47.9 b
M	210 ± 34.0 a	461 ± 45.2 a	595 ± 56.6 a	374 ± 45.6 a
Variety				
Fild	169 ± 20.8 b	664 ± 50.7 a	1018 ± 62.2 a	424 ± 63.7 a
Ob Rot	39 ± 3.5 c	144 ± 16.2 c	267 ± 16.0 b	324 ± 35.2 ab
Rub	77 ± 8.7 c	236 ± 23.5 b	343 ± 16.2 b	274 ± 25.4 b
ZOR	250 ± 32.5 a	292 ± 25.1 b	272 ± 26.6 b	171 ± 23.3 c
ANOVA *p*-values				
Main Effects				
yr	**0.021**	**0.016**	NS	**0.006**
fr	NS	NS	NS	NS
ft	**<0.001**	**<0.001**	**<0.001**	**0.021**
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	**<0.001**	NS	NS	NS
fr:ft	**0.014**	**0.043**	NS	NS
yr:var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
fr:var	NS	NS	NS	NS
ft:var	**<0.001**	NS	NS	NS
yr:fr:ft	NS	NS	NS	NS
yr:fr:var	NS	NS	**0.012**	NS
yr:ft:var	**0.004**	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

Table 3.3.7. Interaction means ±SE for the effects of fertiliser rate and fertiliser type on the Area Under Disease Progress Curve (AUDPC) for yellow stripe rust (*Puccinia striiformis*) on Leaf 1 and Leaf 2.

	Yellow Rust AUDPC Leaf 1			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
50kg N/ha	103 ± 23.1 Aa	107 ± 26.4 Aa	121 ± 29.5 Aa	168 ± 35.5 Ba
100kg N/ha	100 ± 25.5 Abc	87 ± 16.3 Ac	131 ± 32.0 Abc	253 ± 57.5 Aa
	Yellow Rust AUDPC Leaf 2			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
50kg N/ha	228 ± 30.5 Ab	267 ± 49.8 Ab	322 ± 64.9 Ab	400 ± 55.3 Aa
100kg N/ha	341 ± 61.4 Abc	250 ± 49.0 Ac	305 ± 58.1 Abc	522 ± 70.6 Aa

Means labelled with the same capital letter within the same column and the same lowercase letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

Table 3.3.8. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for septoria leaf blotch (*Septoria tritici)* on spelt leaves.

	Leaf 1	**Leaf 2**	**Leaf 3**	**Leaf 4**
Year				
2015	1 ± 0.7	0 ± 0.0	0 ± 0.0	0 ± 0.1
2016	83 ± 9.9	660 ± 45.2	590 ± 47.5	351 ± 41.4
Fertiliser Rate				
0kg N/ha	27 ± 9.1	280 ± 78.1	341 ± 101.2	234 ± 86.1
50kg N/ha	42 ± 8.8	367 ± 50.0	273 ± 43.6	149 ± 31.6
100kg N/ha	45 ± 8.4	306 ± 40.3	306 ± 43.1	187 ± 35.3
Fertiliser Type				
BD	45 ± 11.7	348 ± 65.6	285 ± 61.3	179 ± 46.2
CS	43 ± 13.4	392 ± 70.1	257 ± 55.1	194 ± 49.2
FYM	45 ± 12.2	336 ± 67.4	320 ± 69.5	179 ± 52.7
M	42 ± 11.5	270 ± 53.2	296 ± 59.4	121 ± 41.4
Variety				
Fild	18 ± 3.7 b	518 ± 78.3 a	124 ± 50.0 c	0 ± 0.0 c
Ob Rot	9 ± 2.2 b	75 ± 11.3 c	282 ± 43.3 b	415 ± 60.2 a
Rub	21 ± 4.8 b	221 ± 39.7 b	402 ± 66.3 a	198 ± 47.4 b
ZOR	118 ± 18.3 a	507 ± 67.3 a	372 ± 67.4 ab	89 ± 37.5 bc
ANOVA *p*-values				
Main Effects				
yr	**0.041**	**0.005**	**0.008**	**0.006**
fr	NS	NS	NS	NS
ft	NS	NS	NS	NS
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	NS	NS	NS	NS
fr:ft	NS	NS	NS	NS
yr:var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
fr:var	NS	NS	**0.028**	NS
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	NS	NS
yr:fr:var	NS	NS	**0.028**	NS
yr:ft:var	NS	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

3.3.5 GRAIN MILLING QUALITY

3.3.5.1 SPECIFIC WEIGHT

Significant main effects of year ($p < 0.001$) and fertiliser type ($p = 0.037$) were detected for specific weight; specific weight was much higher in 2016 than 2015 and biogas digestate had the highest specific weight across fertiliser types but differences were not significantly different based on post-hoc tests (Table 3.3.9). Highly significant main effects of variety ($p < 0.001$) were detected for specific weight; specific weight was significantly higher than all other varieties for Rubiota and significantly lower than all other varieties for Oberkulmer Rotkorn (Table 3.3.9).

3.3.5.2 PROTEIN CONTENT

Highly significant main effects of year, fertiliser type and variety ($p < 0.001$) were detected for protein content; grain protein was much higher in 2016 than 2015, cattle slurry protein was the highest across all fertiliser types, though biogas digestate was not significantly different and Oberkulmer Rotkorn and Rubiota had the highest protein levels while Filderstolz protein was significantly lower than for all other varieties (Table 3.3.9).

Significant interaction effects of fertiliser type and variety ($p = 0.028$) were detected for grain protein content (Table 3.3.9); Oberkulmer Rotkorn and Rubiota had the highest protein content when fertilised with biogas digestate and mineral N (Table 3.3.10).

3.3.5.3 HAGBERG FALLING NUMBER

Significant main effects of year ($p = 0.016$) and fertiliser type ($p = 0.031$) were detected for Hagberg Falling Number; HFN was higher in 2015 than 2016 and cattle slurry had the highest HFN across fertiliser types but differences were not significantly different based on post-hoc analysis (Table 3.3.9). Highly significant main effects of variety ($p < 0.001$) were detected for HFN; Filderstolz and Rubiota had the highest HFNs while ZOR HFN was significantly lower than all other varieties (Table 3.3.9).

Highly significant interaction effects of year and variety ($p < 0.001$) were detected for HFN (Table 3.3.9); Rubiota had the highest HFN in 2015 across all varieties and years while Oberkulmer Rotkorn had a significantly lower HFN in 2016 compared with all other varieties (Table 3.3.11).

Table 3.3.9. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the specific weight, protein content and Hagberg Falling Number (HFN) of spelt grain.

	Specific Weight (kg/hl)	**Protein (%)**	**HFN (s)**
Year			
2015	73.3 ± 0.17	12.6 ± 0.09	263 ± 6.0
2016	77.3 ± 0.10	16.0 ± 0.11	210 ± 5.2
Fertiliser Rate			
0kg N/ha	74.9 ± 0.54	13.9 ± 0.34	*NA*
50kg N/ha	75.4 ± 0.23	14.1 ± 0.20	*NA*
100kg N/ha	75.3 ± 0.22	14.5 ± 0.17	236 ± 4.6
Fertiliser Type			
BD	75.7 ± 0.29 a	14.5 ± 0.26 a	235 ± 9.1 a
CS	75.2 ± 0.33 a	14.0 ± 0.27 b	245 ± 9.7 a
FYM	75.4 ± 0.35 a	14.0 ± 0.23 b	242 ± 8.3 a
M	75.2 ± 0.29 a	14.8 ± 0.28 a	225 ± 9.8 a
Variety			
Fild	75.5 ± 0.18 b	13.2 ± 0.19 c	255 ± 6.2 a
Ob Rot	74.2 ± 0.36 c	14.8 ± 0.26 a	230 ± 9.8 b
Rub	76.2 ± 0.15 a	14.8 ± 0.25 a	259 ± 11.3 a
ZOR	75.3 ± 0.41 b	14.2 ± 0.23 b	202 ± 4.4 c
ANOVA *p*-values			
Main Effects			
yr	**<0.001**	**<0.001**	**0.016**
fr	NS	NS	NA
ft	**0.037**	**<0.001**	**0.031**
var	**<0.001**	**<0.001**	**<0.001**
Interactions			
yr:fr	NS	**0.025**	*NA*
yr:ft	**0.018**	NS	NS
fr:ft	NS	NS	*NA*
yr:var	**<0.001**	**<0.001**	**<0.001**
fr:var	NS	NS	*NA*
ft:var	NS	**0.028**	NS
yr:fr:ft	NS	**0.042**	*NA*
yr:fr:var	**0.032**	NS	*NA*
yr:ft:var	NS	NS	NS
fr:ft:var	NS	NS	*NA*
yr:fr:ft:var	NS	NS	*NA*

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs. HFN was not analysed for Low or Zero rate fertiliser, therefore the results of a three-way ANOVA are presented here (yrxftxvar).

Table 3.3.10. Interaction means ±SE for the effects of variety and fertiliser type on spelt protein content.

	Protein (%)			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
Filderstolz	13.3 ± 0.38 Cab	12.9 ± 0.44 Cb	13.1 ± 0.34 Bab	13.6 ± 0.45 Ca
Ob Rotkorn	15.3 ± 0.55 Aa	14.6 ± 0.59 Aa	14.1 ± 0.51 Ab	15.6 ± 0.60 Aa
Rubiota	15.3 ± 0.56 Aa	14.5 ± 0.55 Ab	14.4 ± 0.48 Ab	15.5 ± 0.56 Aa
ZOR	14.2 ± 0.42 Bab	13.9 ± 0.54 Bb	14.2 ± 0.48 Aab	14.6 ± 0.47 Ba

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

Table 3.3.11. Interaction means ±SE for the effects of year and variety on spelt Hagberg Falling Number.

	Hagberg Falling Number (s)			
	Filderstolz	**Ob Rotkorn**	**Rubiota**	**ZOR**
2015	262.7 ± 5.24 Ab	274.6 ± 3.33 Ab	315.6 ± 7.02 Aa	197.4 ± 6.63 Ac
2016	246.9 ± 11.01 Aa	185.5 ± 11.01 Bc	202.8 ± 7.24 Bbc	206.2 ± 5.66 Ab

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

3.3.6 GRAIN NUTRIENT QUALITY

3.3.6.1 MICRONUTRIENT QUALITY

Highly significant main effects of year (p <0.001) were detected for calcium, copper and iron and significant main effects of year were detected for manganese ($p = 0.027$) and zinc ($p = 0.001$); all micronutrient quantities were significantly higher in 2016 than 2015 (Table 3.3.12). Significant main effects of fertiliser type were detected for calcium ($p = 0.001$), copper (p <0.001), iron ($p = 0.002$) and zinc ($p = 0.003$); mineral N and biogas digestate had significantly higher copper levels, mineral N and cattle slurry had significantly higher calcium and cattle slurry had significantly lower amounts of zinc and mineral N and biogas digestate had higher amounts of iron but differences were not significant based on post-hoc tests (Table 3.3.12). Highly significant main effects of variety (p <0.001) were detected for all measured micronutrients; Oberkulmer had significantly higher concentrations of copper, iron, manganese and zinc and Rubiota had significantly higher concentrations of calcium (Table 3.3.12).

3.3.6.2 MACRONUTRIENT QUALITY

Significant main effects of year were detected for potassium ($p = 0.004$), magnesium ($p = 0.002$), phosphorus ($p = 0.003$) and sulphur (p <0.001); all macronutrient quantities were significantly higher in 2016 than in 2015 (Table 3.3.13). Significant main effects of fertiliser rate were detected for sulphur ($p = 0.045$), which was significantly higher in samples fertilised at 100 kgN/ha (Table 3.3.13). Highly significant main effects of fertiliser type ($p < 0.001$) were detected for sulphur; mineral N and biogas digestate had significantly higher sulphur content than other input types (Table 3.3.13). Highly significant main effects of variety ($p < 0.001$) were detected for all measured macronutrients; Oberkulmer and Rubiota had significantly higher concentrations of magnesium, phosphorus and sulphur and Filderstolz had significantly higher potassium content (Table 3.3.13).

3.3.6.3 TOTAL PHENOLIC CONTENT

Highly significant main effects of year and variety ($p < 0.001$) were detected for total phenolic content in spelt grain; TPC was significantly higher in 2016 than 2015 and Filderstolz had significantly higher TPC while Oberkulmer Rotkorn had significantly lower TPC than all other varieties (Table 3.3.14).

Highly significant interaction effects of year and variety ($p < 0.001$) were detected for TPC (Table 3.3.14); Filderstolz had the highest phenolic content across all varieties in both years while Oberkulmer Rotkorn had the lowest TPC in 2015 and ZOR had the lowest in 2016 (Table 3.3.15).

Table 3.3.12. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on micronutrient concentration (mg/kg) of spelt grain.

	Ca	**Cu**	**Fe**	**Mn**	**Zn**
Year					
2015	250 ± 2.4	4.97 ± 0.053	36.1 ± 0.47	25.4 ± 0.29	40.2 ± 0.46
2016	350 ± 2.1	6.45 ± 0.042	49.2 ± 0.46	28.6 ± 0.43	48.1 ± 0.46
Fertiliser Rate					
0kg N/ha	303 ± 11.1	5.70 ± 0.189	43.5 ± 1.55	27.3 ± 0.80	45.2 ± 1.37
50kg N/ha	301 ± 5.0	5.68 ± 0.090	42.1 ± 0.78	27.3 ± 0.46	44.0 ± 0.65
100kg N/ha	299 ± 5.0	5.74 ± 0.073	43.0 ± 0.74	26.6 ± 0.37	44.0 ± 0.53
Fertiliser Type					
BD	296 ± 6.7 b	5.78 ± 0.109 a	43.4 ± 1.05 a	26.3 ± 0.61	43.8 ± 0.85 ab
CS	300 ± 7.0 ab	5.56 ± 0.129 b	41.6 ± 1.06 a	26.7 ± 0.58	42.6 ± 0.89 b
FYM	295 ± 7.1 b	5.59 ± 0.121 b	41.8 ± 1.04 a	27.0 ± 0.58	45.0 ± 0.85 a
M	307 ± 7.5 a	5.90 ± 0.099 a	43.4 ± 1.16 a	27.6 ± 0.58	44.6 ± 0.72 a
Variety					
Fild	267 ± 6.9 c	5.08 ± 0.105 c	36.0 ± 0.87 c	22.4 ± 0.41 d	37.8 ± 0.54 c
Ob Rot	306 ± 5.8 b	6.05 ± 0.111 a	46.5 ± 0.88 a	30.8 ± 0.54 a	48.2 ± 0.74 a
Rub	318 ± 6.2 a	5.68 ± 0.106 b	43.5 ± 0.82 b	26.6 ± 0.40 c	45.2 ± 0.62 b
ZOR	309 ± 6.5 b	6.03 ± 0.079 a	44.7 ± 1.03 b	28.1 ± 0.32 b	45.4 ± 0.73 b
ANOVA					
Main Effects					
yr	**<0.001**	**<0.001**	**<0.001**	**0.027**	**0.001**
fr	NS	NS	NS	NS	NS
ft	**0.001**	**<0.001**	**0.002**	NS	**0.003**
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions					
yr:fr	NS	**0.003**	NS	NS	**0.031**
yr:ft	NS	**<0.001**	NS	NS	**0.003**
fr:ft	NS	NS	NS	NS	**0.016**
yr:var	**0.003**	**<0.001**	**<0.001**	**<0.001**	NS
fr:var	NS	NS	NS	**0.008**	NS
ft:var	**0.022**	NS	NS	NS	**0.009**
yr:fr:ft	NS	NS	NS	NS	NS
yr:fr:var	**0.038**	NS	NS	**0.007**	NS
yr:ft:var	NS	NS	NS	NS	**0.045**
fr:ft:var	NS	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	**0.017**	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Zero treatments were not included in the ANOVAs.

Table 3.3.13. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on macronutrient concentration (mg/g) of spelt grain.

	K	**Mg**	**P**	**S**
Year				
2015	3.66 ± 0.025	1.15 ± 0.006	4.01 ± 0.024	1.47 ± 0.011
2016	3.96 ± 0.046	1.31 ± 0.012	4.45 ± 0.047	1.73 ± 0.015
Fertiliser Rate				
0kg N/ha	3.85 ± 0.072	1.24 ± 0.022	4.29 ± 0.080	1.58 ± 0.031
50kg N/ha	3.80 ± 0.047	1.22 ± 0.014	4.21 ± 0.051	1.58 ± 0.021
100kg N/ha	3.81 ± 0.037	1.23 ± 0.011	4.23 ± 0.036	1.62 ± 0.015
Fertiliser Type				
BD	3.83 ± 0.052	1.22 ± 0.015	4.23 ± 0.052	1.62 ± 0.023 ab
CS	3.79 ± 0.081	1.20 ± 0.024	4.17 ± 0.086	1.53 ± 0.034 c
FYM	3.79 ± 0.049	1.24 ± 0.014	4.24 ± 0.052	1.58 ± 0.021 bc
M	3.79 ± 0.053	1.25 ± 0.016	4.24 ± 0.055	1.67 ± 0.023 a
Variety				
Fild	4.12 ± 0.030 a	1.24 ± 0.011 b	4.28 ± 0.031 b	1.48 ± 0.018 c
Ob Rot	3.90 ± 0.064 b	1.29 ± 0.023 a	4.47 ± 0.077 a	1.66 ± 0.032 a
Rub	3.97 ± 0.031 b	1.26 ± 0.012 ab	4.43 ± 0.039 a	1.69 ± 0.019 a
ZOR	3.24 ± 0.016 c	1.12 ± 0.010 c	3.74 ± 0.024 c	1.57 ± 0.018 b
ANOVA *p*-values				
Main Effects				
yr	**0.004**	**0.002**	**0.003**	**<0.001**
fr	NS	NS	NS	**0.045**
ft	NS	NS	NS	**<0.001**
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	NS	NS	NS	NS
fr:ft	NS	NS	**0.035**	**0.038**
yr:var	**<0.001**	NS	NS	NS
fr:var	NS	NS	NS	NS
ft:var	NS	**0.050**	NS	**0.091**
yr:fr:ft	NS	NS	NS	NS
yr:fr:var	NS	NS	NS	NS
yr:ft:var	**0.023**	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

Table 3.3.14. Main effect means, ±SE and *p*-values for the effects and interactions of fertiliser type and variety on total phenolic content (TPC) of spelt grain.

	TPC (mg/kg)
Year	
2015	526 ± 9.6
2016	1646 ± 17.1
Fertiliser Type	
BD	1077 ± 101.0
CS	1103 ± 105.1
FYM	1087 ± 103.2
M	1075 ± 100.6
Variety	
Fild	1191 ± 103.0 a
Ob Rot	1039 ± 109.0 c
Rub	1083 ± 106.6 b
ZOR	1030 ± 87.3 c
ANOVA *p*-values	
Main Effects	
yr	**<0.001**
ft	NS
var	**<0.001**
Interactions	
yr:ft	NS
yr:var	**<0.001**
ft:var	NS
yr:ft:var	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05).

Table 3.3.15. Interaction means ±SE for the effects of year and variety on total phenolic content (TPC) of spelt grain.

	TPC (mg/kg)			
	Filderstolz	**Ob Rotkorn**	**Rubiota**	**ZOR**
2015	624.1 ± 8.93 Ba	438.3 ± 8.02 Bd	492.0 ± 8.14 Bc	548.9 ± 7.97 Bb
2016	1758.8 ± 29.55 Aa	1638.7 ± 32.48 Ab	1673.1 ± 20.03 Ab	1511.8 ± 22.46 Ac

Means labelled with the same capital letter within the same column and the same lower case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

3.3.7 MULTIVARIATE ANALYSIS

The bi-plot of the RDA (Figure 3.3.1) shows the relationship between weather, fertiliser treatment, variety and spelt yield and quality parameters. Between them, the included drivers explained 65.3%, axis 1 explained 56.3% and axis 2 a further 7.2% of the variation in the dataset. Radiation was identified as the strongest driver ($p = 0.002$) while variety ($p = 0.002$), mineral N fertiliser at low rate ($p = 0.036$) and high rate ($p = 0.004$) applications and biogas digestate at high rate applications ($p = 0.034$) were also identified as important drivers.

Radiation, the strongest driver, was closely associated with the positive axis 2. Fertiliser treatments were grouped at the axes intersection with both biogas, lower rate mineral N and higher rate cattle slurry treatments along the positive axis 1 with grains/ear and both farm-yard manure composts, higher rate mineral N and lower rate cattle slurry along the negative axis 1 but positive axis 2. Yield, between both positive axes, was grouped with thousand grain weight and ears/m2 while harvest index was associated with the negative axis 1 and high rate mineral N fertility. Varieties were strongly associated with axis 1 and split so that the shorter varieties, ZOR and Filderstolz, were on the negative side while the taller varieties, Rubiota and Oberkulmer Rotkorn were on the positive side, along with plant height. Protein content and specific weight were associated with the negative axis 2. Yellow rust on the flag leaf was associated with the positive axis 2 and leaf 1 yellow rust disease was strongly associated with positive axis 2 and negative axis 1. Leaf 3 yellow rust was associated with negative axis 1 and low rate farm-yard manure compost.

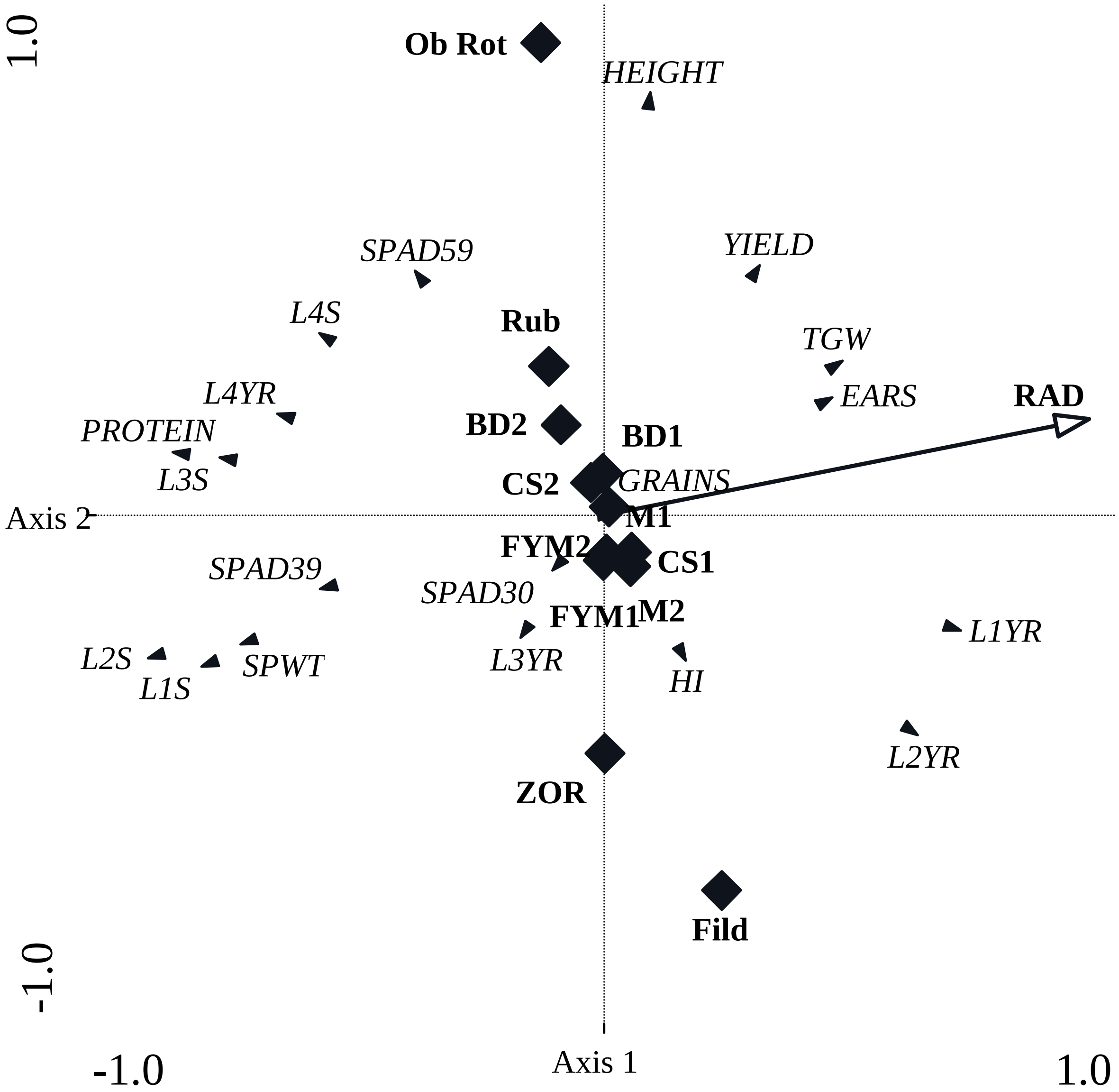

Figure 3.3.1. Bi-plot derived from redundancy analysis showing associations between climatic drivers (RAD—radiation), fertiliser treatments (BD—biogas digestate, CS—cattle slurry, FYM—composted farm-yard manure and M—mineral N at rate 1—50kgN/ha and rate 2—100kgN/ha) and variety (Fild—Filderstolz, Ob Rot—Oberkulmer Rotkorn, Rub—Rubiota and ZOR— Zuercher Oberlaender Rotkorn) on yield, plant height (HEIGHT), yield components (EARS—ears/m^2, GRAINS—grains/ear and TGW—thousand grain weight), harvest index (HI), SPAD readings (SPAD30—SPAD at GS30, SPAD39—SPAD at GS39 and SPAD59—SPAD at GS59), disease levels (YR—yellow rust and S—*Septoria tritici* on L1 to L4—leaf 1 to leaf 4) and quality (PROTEIN—protein and SPWT—specific weight) of spelt grown in the 2015-2016 field trial.

3.4 DISCUSSION

3.4.1 GRAIN HARVEST

3.4.1.1 GRAIN YIELD

Grain yield was significantly higher in 2015, reflecting overall differences in arable crop production in the UK during the two growing seasons. 2015 was an exceptionally productive year for cereals as wheat yields increased by 4.6% from 2014, resulting in the highest UK average wheat yields on record (DEFRA, 2015). Comparatively, UK wheat yields decreased by 12% from 2015 to 2016 (DEFRA, 2016). In the trial, spelt yield was 20.5% lower in 2016 (2.86 t/ha) compared to 2015 (3.60 t/ha). Radiation levels were the major factor contributing to lower yields in the second year, as 2015 had 6% more sunshine hours annually and 34% more sunshine during June in Northeast England compared to 2016 (MetOffice, 2018b). Sunlight absorption is a key factor in cereal crop yields, as both crop growth and final yields increase with higher radiation absorption, especially from April through July (Gallagher and Biscoe, 1978). Based on the field station weather data collected at Nafferton farm, total radiation was higher over the full year for 2015 and specifically over April, May, June and July in 2015 (1937 MJ/m^2) compared to 2016 (1342 MJ/m^2) (Table A.1., Appendix A). The RDA bi-plot also identified radiation as the key driver to explain overall variation in the full two-year dataset, contributing to differences in yield and associated parameters including TGW and $ears/m^2$. Cereal yields increase with increased radiation in spring and summer in European production systems (Peltonen-Sainio *et al*., 2010a; Kristensen *et al*., 2011), and in the absence of major weather anomalies between the two trial years, higher radiation was the main contributor to higher spelt yields in 2015 compared to 2016.

A Croatian trial with two spelt varieties found that higher than average precipitation and lower mean monthly air temperature contributed to lower annual yields (Pospišil *et al.*, 2011) and spelt grown in different trials in Slovenia had significantly lower yields in years with significant rain events (Turinek *et al.*, 2010; Bavec *et al.*, 2012). While the results of these trials focused on precipitation anomalies, higher than average rainfall results in low radiation, which also impacts overall grain yield. In the field trial, total rainfall was higher in the 2016 trial year (878 mm) than 2015 (642 mm) (Table A.1., Appendix A), but average annual rainfall in Northeast England falls between 600mm and 1000mm (MetOffice, 2016), so both years had typical rainfall and in the northern part of the UK rainfall does not usually limit crop productivity.

Similar to other cereal crops, spelt yield benefits from application of fertiliser. Studies in Poland (Andruszczak *et al.*, 2011) and Greece (Koutroubas *et al.*, 2012) had higher spelt yields with higher rates of mineral N fertiliser, although applications in these studies were much lower than typical for commercial wheat (100kg N/ha or less). Spelt grown in an organic transition rotation had significantly higher yields with manure and compost applications than with no inputs (Caldwell *et al.*, 2014) and in a comparison of spelt grown in different low-input production systems, yields were highest in a biodynamic system with compost applications (Turinek *et al.*, 2010). Similar benefits of fertility amendments were evident in this field trial. Biogas digestate was the most productive fertiliser, resulting in significantly higher yields (3.64 t/ha) than all other fertiliser input types. Digestate supplies more plant readily available N than other organic fertilisers and animal manures (Tambone *et al.*, 2010; Alburquerque *et al.*, 2012; Möller and Müller, 2012; Wentzel *et al.*, 2015), which was reflected in significantly higher SPAD readings compared to the two composts. The SPAD readings also demonstrate that biogas digestate was similar to mineral N in efficiency of utilisation by the spelt crop, resulting in no significant difference between SPAD readings of plants fertilised with biogas digestate and mineral N, and even significantly higher readings for digestate at one date. This offers clear evidence of the potential of digestate as an organic fertiliser, which requires a Derogation for use under current organic farming regulations (EU Commission Regulation No. 142/2011).

Oberkulmer Rotkorn, the old Swiss landrace, produced the highest yield (3.74 t/ha), while Filderstolz, the modern semi-dwarf German variety, had the lowest yield (2.60 t/ha) across all varieties and years. The varietal yield differences were particularly impacted by yellow rust disease levels, which were lowest for Oberkulmer and significantly higher for Filderstolz than all other varieties on Leaf 2 and Leaf 3, contributing to its lower yields.

The yield differences between Oberkulmer Rotkorn and Filderstolz are particularly interesting, as Filderstolz was specifically bred as a cross with a dwarfing gene from wheat. European and UK breeding programmes have long sought to develop modern varieties, particularly of wheat, with shorter stems to increase grain yields (Flintham *et al.*, 1997; Austin *et al.*, 2009) and first generation wheat x spelt hybrids have high heterosis on grain yield parameters (Winzeler *et al.*, 1993). While hybrids continue to be developed, there is increasing interest in maintaining landraces, particularly for disease and pest resistance and nutrient-use efficiency characteristics (Newton *et al.*, 2010). The nature of landraces with saved seed grown year after year means they have become adapted to their environment and acquired increased resistance to many local pests and diseases (Newton *et al.*, 2010). The results from this trial indicate that the higher yellow rust resistance of the old landrace, Oberkulmer, was a key factor contributing to the higher yields compared to the modern short-stemmed variety Filderstolz.

3.4.1.2 PLANT HEIGHT

Differences in spelt plant height reflected grain yield results, as plant height was significantly higher in 2015 (123.3 cm) compared to 2016 (112.2 cm) and the taller varieties (Oberkulmer Rotkorn and Rubiota) were also higher yielding. The significant differences in plant height by variety are expected, as Oberkulmer Rotkorn (135.0 cm) and Rubiota (135.0 cm) are both tall-growing varieties, while ZOR (107.5 cm) and, as discussed, Filderstolz (93.6 cm) are shorter genotypes. The taller landrace varieties, e.g. Oberkulmer Rotkorn, can outcompete weeds, and although this creates a higher risk of lodging, this was low in both years of the trial, likely due to the lower rates of N fertility than are generally used in conventional wheat production. Similarly, Konvalina *et al.* (2010) found that taller spelt plants were not as inclined to lodging as emmer and bread wheats.

3.4.1.3 HARVEST INDEX

Harvest index is a ratio of final grain yield to total plant biomass and is used as an indicator of reproductive efficiency. In the UK, growers typically aim for a benchmark HI of 50% for winter wheat, indicating that the majority of the crop mass is diverted to the grain (AHDB, 2018b). Due to its hull, spelt harvest index is expected to be much lower than wheat, as a larger portion of the total biomass will be in the chaff once the grain has been de-hulled.

Overall, the average harvest index for all spelt varieties over the two-year trial was 31.15%, which is much lower than typical values for wheat, but not unusual for spelt. European studies have identified spelt harvest index in the range of 29-41% (Winzeler *et al.*, 1993; Konvalina *et al.*, 2010; Koutroubas *et al.*, 2012; Konvalina *et al.*, 2014), much lower than bread wheat, but similar to HI in the field trial. While HI is a relevant indicator of production efficiency, it is worth nothing that straw is valuable as bedding material for livestock and taller straw produced by spelt is considered beneficial, especially in organic systems, as bedding and to contribute organic matter to soil fertiliser inputs (Konvalina *et al.*, 2014).

There were no significant main effects for year or fertility regimes, although significant interaction effects existed for fertiliser rate and type. Spelt HI with mineral N fertiliser was significantly higher at low rate (32.7%) compared to high rate fertiliser (27.0%), which was not seen for any other fertiliser type. Higher N application in studies of different wheat genotypes typically results in lower mean HI (Pearman *et al.*, 1978; Ehdaie and Waines, 2001) and contributes to increased overall N losses in the crop (Kanampiu *et al.*, 1997). This result highlights the low-input potential of spelt to improve nitrogen-use-efficiency.

Significant differences in HI existed between varieties; Filderstolz had a significantly higher HI (35.7%) compared with all other varieties, likely due to the dwarfing gene present from the spelt-wheat cross. Cereal breeding techniques have long selected for shorter stemmed plants to improve harvest index (Pearman *et al.*, 1978; Austin *et al.*, 1980), which have been implemented in spelt (Winzeler *et al.*, 1993; Longin and Würschum, 2014) and are evident in the results from this trial. Despite higher yields, the taller-stemmed Oberkulmer Rotkorn and Rubiota varieties had significantly lower HI (28.8% and 27.7% respectively) than the wheat-cross Filderstolz and the shorter-stemmed ZOR (32.4%). This varietal effect was also exhibited in significant interactions between year and variety. In 2016, all varieties had a lower HI in 2016 except Filderstoltz, which had a significantly higher HI in 2016 (39.3%) compared to 2015 (31.3%).

3.4.2 YIELD COMPONENTS

Considering the yield components for spelt, higher yield in 2015 is reflected in significantly higher ears/m^2 (351), grains/m^2 (5110) and heavier grain (TGW 49.3g) in 2015 compared to 2016 (238 ears/m^2, 3405 grains/m^2 and TGW 44.7g). In terms of fertiliser type, mineral N had significantly lower ears/m^2 (265) and grains/m^2 (3864) than other fertiliser types, which is reflected in lower combinable grain yields for mineral N than biogas digestate. The RDA indicates that radiation (and overall weather differences between years) drove yield components and that yield components were closely associated with yield (Figure 3.3.1).

Oberkulmer Rotkorn had the highest TGW (49.7g), which was significantly higher than all other varieties; ZOR TGW was significantly lower than other varieties, at 44.4g. TGW from the two-year trial is comparable to results from other spelt field trials in Europe. In a four-year field experiment of eight spelt varieties in Slovakia, the average TGW was 43.48g (Lacko-Bartošová *et al.*, 2010), a two-year trial of two spelt varieties in Croatia produced a high TGW of 57.7g for one cultivar and low of 49.7g for the other (Pospišil *et al.*, 2011) and a two-year Polish trial of two winter spelt cultivars had TGW of 44.6g and 45.8g (Andruszczak *et al.*, 2011).

3.4.3 SPAD

SPAD readings to measure cholorphyll content are used as an indicator of leaf N content due to the linear relationship between leaf nitrogen and chlorophyll content in plants (Evans, 1989).

While exploring these results can provide additional insight into the effect of different fertiliser regimes on crop production, using a SPAD meter comes with limitations, as discussed in the methodology (Section 3.2.2.1). Although spelt SPAD readings were significantly higher in 2016 compared with 2015 at GS39 and GS59, the variation between years is difficult to attribute to a specific factor because chlorophyll content is not uniformetly distributed in plant leaves, which contributes to variation in SPAD meter readings and actual chlorophyll concentration (Parry et al., 2014).

3.4.4 DISEASE SEVERITY

3.4.4.1 YELLOW RUST

Yellow striped rust (*Puccinia striiformis*) was the most prevalent disease affecting spelt over both years (Figure 3.4.1). Disease levels were greater on the top three leaves of plants treated with mineral N, with the highest yellow rust AUDPC occurring on Leaf 3 (AUDPC=595). Similar results were observed at Nafferton farm in a winter wheat trial in which powdery mildew disease levels were higher with synthetic N compared with composted FYM fertilisers (Bilsborrow *et al.*, 2013). This higher incidence of disease from high plant-available N fertility is also evident in interactions between fertiliser rate and fertiliser type. AUDPC for yellow rust was significantly higher in plants fertilised with high rate mineral N fertiliser than all other fertiliser types and rates on both Leaf 1 (AUDPC=253) and Leaf 2 (AUDPC=522.3). This effect of high nitrogen application and disease severity did not appear to impact final yield by fertiliser type or rate, although variety susceptibility to disease did impact yield.

As discussed, Filderstolz had significantly higher disease levels on Leaf 2 (AUDPC=664) and Leaf 3 (AUDPC=1018) and was the lowest yielding variety. In a Croatian trial, spelt yield was significantly higher with the application of fungicide in years when plants experienced high incidence of powdery mildew and leaf rust (Pospišil *et al.*, 2011), reflecting a similar impact of disease susceptibility on final grain yield. Some spelt varieties have demonstrated resistance to yellow rust (Chen, 2005). The highest yielding variety, Oberkulmer Rotkorn, is known to be moderately resistant and has been used to develop yellow rust resistance in wheat x spelt hybrids (Schmid *et al.*, 1994), and this resistance was apparent in the field trial, as Oberkulmer had the lowest levels of disease severity. Breeding for higher-yielding wheat qualities in Filderstolz likely diminished disease resistance, especially compared to a landrace variety like Oberkulmer Rotkorn.

Figure 3.4.1. The spelt trials, with evidence of yellow rust disease and senesced leaves variance by variety. From left to right, the varieties are Oberkulmer Rotkorn, ZOR, Rubiota and Filderstolz.

3.4.4.2 LEAF BLOTCH

Septoria leaf blotch (*Septoria tritici)* was present in the second year of the spelt trial. In 2015, septoria was barely detected on spelt leaves, while disease levels were much higher in 2016 (though not approaching the severity of yellow rust). The higher incidence of disease on plants treated with synthetic N fertilisers was not observed in the septoria AUDPC, but differences in variety susceptibility were apparent. The variety ZOR had significantly higher S*eptoria tritici* disease levels on Leaf 1 (AUDPC=118) than all other varieties and was not significantly different from the varieties with highest disease levels on Leaf 2 (Filderstolz AUDPC=518) and Leaf 3 (Rubiota AUDPC=402). Although septoria AUDPC results were much higher in 2016, the overall septoria severity was much lower than the prevalence of yellow rust in both years and did not appear to have any clear impact on yield results or grain quality.

3.4.5 GRAIN QUALITY

Because spelt is an ancient wheat, millers and bakers use typical wheat quality parameters (Table 3.4.1) to evaluate spelt grain quality for milling and baking. All the varieties included in the trial are suitable for baking, most often for bread, and the primary parameters considered for milling and baking quality are specific weight, protein content and Hagberg Falling Number. Specific weight is a ratio of mass to volume and serves as an indication of potential flour extraction rate. A low specific weight can result from small/shrivelled grains or excess dust/chaff and/or a high moisture content and typically results in a low flour extraction rate (NABIM, 2014). In bread making, proteins form gluten, which determines the viscoelastic properties of a dough (Shewry *et al.*, 2002). Bread makers prefer highly elastic 'strong' dough and check for grain protein content to give an idea of how the resulting dough will perform. HFN is a measure of alpha-amylase activity; a low HFN reflects increasing alpha amylase levels and indicates that the grain has started to mobilise starch and even sprouted pre-harvest. A very low HFN results in bread with poor texture and a sticky crumb while high HFN produces bread with poor volume and dry crumb (Perten, 2016).

Table 3.4.1. UK Minimum Hard Wheat Specifications for specific weight, protein content and Hagberg Falling Number (NABIM, 2018).

Specific weight (kg/hl)	76
Protein (%)	13
Hagberge Falling Number (s)	250

In 2015, UK winter wheat quality was typical, with specific weight and protein levels above the previous three-year average (excluding 2012), although HFN was the lowest average since 2012 (AHDB, 2015). 2016 was an exceptional year for milling-wheat quality with the highest proportion of high-quality milling varieties meeting specifications in 13 years (AHDB, 2016b). Over the two years of the field trial, specific weight and protein were higher in 2015 compared with 2016 nationally and in the North, while HFN was the same over both years nationally but higher in 2016 regionally (Table 3.4.2).

Table 3.4.2. Grain quality for hard-wheat grown in the UK in 2015 and 2016, including country-wide averages and regional averages for the North.

	2015		**2016**	
	UK	**North**	**UK**	**North**
Specific weight (kg/hl)	79.6	79.7	77.2	77.9
Protein (%)	12.6	12.4	13.0	12.9
Hagberg Falling Number (s)	314	304	314	319

Data from Agriculture and Horticulture Development Board (AHDB) Cereal Quality Surveys (AHDB, 2015; AHDB, 2016b)

3.4.5.1 **SPECIFIC WEIGHT**

The UK minimum hard wheat specification for specific weight is 76 kg/hl (Table 3.4.1) and UK milling wheat averages were 79.6 kg/hl in 2015 and 77.2 kg/hl in 2016 (Table 3.4.2). The spelt in the trial met the minimum requirement and UK wheat average in 2016 (77.3 kg/hl), but the 2015 crop fell short (73.3 kg/hl). Regionally, specific weight averages in the North were higher than the national average in 2015 (79.7 kg/hl) and in 2016 (77.9 kg/hl), but the spelt trial results were below the Northern average in both years.

Differences between fertiliser types were not significant, but clear differences in specific weight occurred between varieties. Rubiota had the highest specific weight (76.2 kg/hl), within the specifications, while Oberkulmer Rotkorn had the lowest specific weight of all varieties (74.2 kg/hl), below the minimum hard-wheat specification.

3.4.5.2 **PROTEIN CONTENT**

The UK minimum hard wheat specification for protein content is 13% (Table 3.4.1) and UK milling wheat averages were 12.6% in 2015 and 13.0% in 2016 (Table 3.4.2). The spelt in the trial met the minimum requirement and UK wheat averages in both 2015 (12.6%) and 2016 (16.0%). UK-wide surveys of winter wheat recorded average protein levels in 2016 as the highest in ten years (AHDB, 2016a), and this higher protein content was also present in the field trial spelt. Spelt has been shown to have higher grain protein content in whole grain flour than modern wheats in North America (Abdel-Aal *et al.*, 1995; Ranhotra *et al.*, 1996b; Abdel-Aal *et al.*, 1997) and Europe (Codianni *et al.*, 1996; Bonafaccia *et al.*, 2000; Gomez-Becerra *et al.*, 2010; Moudrý *et al.*, 2011; Filipcev *et al.*, 2013; Stolickova and Konvalina, 2014; Longin *et al.*, 2015; Bernas *et al.*, 2016). Lacko-Bartošová *et al.* (2010) observed that higher air temperature and drought conditions contributed to an increase in storage proteins formed in spelt grains. Although the 2016 climate did not resemble drought, the air temperature was higher and amount of rainfall lower during the growing season compared to 2015 (Table A.1., Appendix A), however the grain protein responds to a dilution effect of yield, so lower protein in 2016 is likely reflective of lower yield in that year.

The higher plant available N fertilisers, biogas digestate and mineral N, resulted in significantly higher protein levels than other fertiliser types (14.5% and 14.8% respectively), which is to be expected because grain protein content is calculated directly from grain N content (Merrill and Watt, 1955). Higher protein content under conventional management with mineral N fertilisers compared with organic fertilisers has also been reported in wheat (Mäder *et al.*, 2007). Spelt is also noted to have the potential to produce high protein grain even with reduced N fertility (Dorval *et al.*, 2015; Longin *et al.*, 2015), and in a year with notably high protein content in UK-grown milling wheat, the 2016 spelt trials produced grains with exceptionally high protein levels.

The taller varieties, Oberkulmer Rotkorn and Rubiota, had the highest protein content (14.8%) while the semi-dwarf Filderstolz had significantly lower protein content (13.2%) to all other varieties. The interaction effects of fertiliser type and variety also reflected the main effects of variety, as Oberkulmer Rotkorn and Rubiota had the highest protein content across all varieties and fertiliser types when fertilised with biogas digestate (15.3%) and mineral N (15.6% and 15.5% respectively). Regardless of differences, all spelt varieties met the standard protein specification for milling wheats.

While these quality parameters do give an indication as to final baking quality, it should be noted that the National Association of British and Irish Flour Millers (NABIM) quality specifications are designated based on the requirements of industrial bread-making. Artisan bakers emphasise that flour quality standards for the Chorleywood Bread Process (reliant on high-energy minerals and chemicals for quick rise white bread) are not relevant for slow-fermentation bread-making (Whitley, 2009; Sobczyk *et al.*, 2017). Alternative grains, including spelt, are of particular interest for sourdough and other artisan baking processes and slow-fermentation bakers are not as reliant on these quality metrics, and can produce well-made loaves with flour of less than 13% protein.

3.4.5.3 HAGBERG FALLING NUMBER

The UK minimum hard wheat specification for Hagberg Falling Number is 250 seconds (Table 3.4.1) and UK milling wheat averaged 314 seconds in both 2015 and 2016 (Table 3.4.2). Although spelt from the trial met minimum specifications in 2015 (263 seconds), grain HFN was below the national and regional averages (for wheat) and failed to meet the minimum requirement in 2016 (210 seconds).

Differences between fertiliser types were not significant, but differences in HFN between varieties were significant. Rubiota and Filderstolz both met minimum requirements (259 and 255 seconds respectively) while ZOR had a significantly lower Falling Number to all other varieties (202 seconds) and Oberkulmer Rotkorn HFN was also below the minimum (230 seconds). The interaction between year and variety shows that Oberkulmer Rotkorn HFN was above the minimum standard in 2015 (274.6 seconds) but was significantly lower in 2016 (185.5 seconds), indicating that the landrace genotype was particularly affected by climatic differences, particularly rainfall prior to harvest, between years.

Cultivar and weather conditions have both been shown to have significant effects on HFN in wheat grown in England (Smith and Gooding, 1999), with higher summer temperatures increasing HFN and higher late summer rainfall decreasing HFN. This relationship between climate and variety has also been observed in spelt, with higher air temperature and drought during grain maturation contributing to higher Falling Numbers (Lacko-Bartošová *et al.*, 2010; Korczyk-Szabó and Lacko-Bartošová, 2012). In both trial years, rainfall was not exceptionally high pre-harvest, but mean air temperature was 4 degrees cooler in August 2016 (11.2°C) compared with August 2015 (15.4°C).

3.4.6 GRAIN NUTRIENT QUALITY

Spelt has been associated with greater nutritional benefits compared with common wheat varieties, including higher mineral content (Stallknecht *et al.*, 1996; Pospišil *et al.*, 2011). While the complete nutrient profile has not been shown to be universally advantageous compared with common wheat, there is evidence that spelt, among other ancient grains, contains higher levels of nutrients often lacking in cereals, including zinc and iron.

3.4.6.1 MICRONUTRIENT QUALITY

Many studies analysing micronutrient quality in spelt focus on zinc and iron, especially with regard to biofortification. Analysis of modern wheats have demonstrated that breeding for higher yields by focusing on shorter cultivars has contributed to grain nutrient dilution, especially in zinc and to a lesser extent iron (Fan *et al.*, 2008; Zhao *et al.*, 2009).

Spelt is considered a source of nutrients compared to common wheat, especially in landraces and varieties that have not been the focus of high-yield/high-input breeding programmes. Studies in North America and Europe found higher zinc concentrations in spelt (ranging from 22.9 to 47.2 mg/kg) than wheat (21.4 to 36.2 mg/kg) (Ranhotra *et al.*, 1995; Grela, 1996; Ranhotra *et al.*, 1996a; Piergiovanni *et al.*, 1997; Ruibal-Mendieta *et al.*, 2005; Zhao *et al.*, 2009; Hussain *et al.*, 2010; Suchowilska *et al.*, 2012; Kwiatkowski *et al.*, 2015). Gomez-Becerra *et al.* (2010) found that many spelt varieties had average zinc and iron quantities of more than 50 mg/kg, indicating the potential for high micronutrients in spelt grain. The spelt from the field trial produced zinc and iron concentrations within the range observed in other studies, with particularly high concentrations of zinc (48.2 mg/kg) and iron (49.2 mg/kg) in 2016. The results of this trial support the promotion of spelt as a wheat alternative with higher availability of zinc and iron.

Variety had a highly significant effect on micronutrient quality, with Rubiota grain producing the highest concentration of calcium (318 mg/kg) and Oberkulmer Rotkorn resulting in the highest concentrations of copper (6.05 mg/kg), iron (46.5 mg/kg), manganese (30.8 mg/kg) and zinc (48.2 mg/kg). In analyses of wheat cultivars, including primitive varieties (spelt, emmer and einkorn), higher concentrations of micronutrients occur in the ancient grains, especially compared with higher yielding modern varieties (Zhao *et al.*, 2009; Hussain *et al.*, 2010). As an old landrace used in many European countries, Oberkulmer is often included in spelt trials and is noted for high micronutrient content compared with other varieties (Ranhotra *et al.*, 1996a; Kraska *et al.*, 2013). The lower micronutrient content of the short-stemmed varieties Filderstolz and ZOR is also reflective of the overall decrease in grain mineral concentrations after the Green Revolution, which has partly been attributed to the wide-adoption of high-yielding short-straw cultivars (Fan *et al.*, 2008).

3.4.6.2 **MACRONUTRIENT QUALITY**

The differences in macronutrient quality between spelt and common wheat are not as extreme as for micronutrients (particularly zinc and iron), but two studies found spelt had higher levels of potassium (4.15-4.33 mg/g), phosphorus (4.17-4.28 mg/g), magnesium (1.27-1.28 mg/g) and sulphur (1.36-1.72 mg/g) (Piergiovanni *et al.*, 1997; Hussain *et al.*, 2010) and others noted that spelt had higher phosphorus (2.92-4.27 mg/g) and magnesium (1.27-1.47 mg/g) (Grela, 1996; Ruibal-Mendieta *et al.*, 2005) and potassium (3.5-3.7 mg/g) (Abdel-Aal *et al.*, 1995) than wheat. The macronutrient contents analysed in the trial fell within the ranges observed in other studies but were not notably higher than concentrations typically found in wheat.

As was the case for micronutrients, macronutrient content differences were highly significant for variety, with Filderstolz producing the highest potassium concentrations (4.12 mg/g) and Oberkulmer Rotkorn and Rubiota producing the highest magnesium (1.29 and 1.26 mg/g), phosphorus (4.47 and 4.43 mg/g) and sulphur (1.66 and 1.69 mg/g) concentrations. Similar to micronutrients, ancient varieties of wheat have higher macronutrient contents compared with modern common wheats and plant height has also been shown to be positively correlated with magnesium and phosphorus concentrations (Hussain *et al.*, 2010). The landrace Oberkulmer Rotkorn had a strong nutrient profile across both micro- and macronutrients and, along with Rubiota, is a taller genotype, which proved an additional advantage for nutrient content.

3.4.6.3 **TOTAL PHENOLIC CONTENT**

Wheat is considered a primary source of polyphenols, with the highest concentrations in the bran (Barron *et al.*, 2007) and ferulic acid identified as the predominant phenolic acid in wheat bran (Zhou *et al.*, 2004a; Zhou *et al.*, 2004b; Zhou *et al.*, 2005; Moore *et al.*, 2006; Mpofu *et al.*, 2006). Total phenolic content varies widely based on species and genotype, with some studies reporting that ancient wheats have higher TPC than common wheat. Multiple studies report that emmer produces the most phenolics among wheats (Serpen *et al.*, 2008; Lachman *et al.*, 2012), while emmer, einkorn and spelt were all noted as producing high TPC compared with common wheats (Abdel-Aal and Rabalski, 2008). Conversely, Brandolini *et al.* (2013) and Li *et al.* (2008) found that wheat had higher phenolic acid content than einkorn, emmer and spelt, while other analyses concluded that spelt does not differ significantly from wheat in phenolic compounds (Zieliński *et al.*, 2007; Shewry and Hey, 2015). Despite these different conclusions, all these studies agree that there is great variation in polyphenolic content by variety and environment.

Over the two years of the field trial, total phenolic content was significantly higher in 2016 (1646 mg/kg) than 2015 (526 mg/kg). Studies of different wheat cultivars have found that besides variety, environment has a significant influence on TPC, which contributes to differences in polyphenols between both location (Moore *et al.*, 2006; Mpofu *et al.*, 2006; Shewry *et al.*, 2010) and trial year (Stracke *et al.*, 2009; Heimler *et al.*, 2010; Lachman *et al.*, 2011; Lachman *et al.*, 2012; Brandolini *et al.*, 2013). Stracke *et al.* (2009) measured year-to-year differences in total phenolics in wheat of up to 55%, with a range of TPC from 283 mg/kg to 1262 mg/kg across all years and varieties. The difference in spelt TPC from the field trial is dramatic; phenolic content was more than 200% higher in 2016 compared with 2015. This difference is difficult to account for based on previous studies. Some negative correlations between TPC and lower rainfall (Lachman *et al.*, 2011) and high temperatures pre-harvest (Moore *et al.*, 2006; Heimler *et al.*, 2010; Lachman *et al.*, 2011) have been observed in wheats, while analysis of wheat grown at Nafferton farm found that high solar radiation and low relative humidity contributed to higher phenolic concentrations in wheat leaves (Rempelos *et al*., 2018). In the field trial, differences in August rainfall and temperature between the two trial years were minimal, though 2015 did have 27% lower annual rainfall than 2016 (Table A.1., Appendix A), which may reflect lower humidity in 2016. The effects of higher radiation levels in 2015 contributed to higher yields, but this did not translate to higher TPC. Ultimately, the difference in spelt TPC from 2015 to 2016 may reflect a yield dilution effect, as yields were significantly higher and grains were significantly larger (based on TGW) in 2015. Phenolic content was not a primary focus of this trial, but as a source of polyphenols, future research should consider the causes of TPC variation in spelt varieties.

Differences in TPC between fertiliser input types were not significant and evidence indicates that management practices are not as influential on phenolic content in wheat compared with genotype and environment (Moore *et al.*, 2006; Mpofu *et al.*, 2006; Stracke *et al.*, 2009; Lachman *et al.*, 2012). Overall farm management practices may have an effect, as total phenolic content is higher in organic compared to conventional systems for both spelt and wheat (Kwiatkowski *et al.*, 2015). The correlation between higher phenolic content and organic management in crops is also noted by Barański *et al.* (2014), although this is largely attributed to crop protection methods, which were not a factor in this trial.

Unlike mineral content, the land race variety Oberkulmer, along with the modern short-stemmed ZOR, had significantly lower phenolic content (1039 and 1030 mg/kg respectively) than all other varieties, while the modern spelt x wheat cross, Filderstolz, had the highest phenolic content (1191 mg/kg) across all varieties. Phenolic compounds are produced by plants as a response to stress, including as a reaction to disease (Nicholson and Hammerschmidt, 1992). Filderstolz was the most susceptible to yellow rust disease throughout the trial and the crops natural response to this stress may have contributed to higher concentrations of phenolics in the grain.

3.5 CONCLUSIONS

The results provide valuable data about and experience of growing European spelt varieties in Northeast England, which can be used to recommend preferred management practices, including variety choice and fertiliser inputs, for spelt production.

In particular, the taller-stemmed varieties, Oberkulmer Rotkorn and Rubiota, were well-suited to the variable climatic conditions and leaf disease susceptibility, producing higher yields and higher quality grains than the shorter genotypes.

The results of the field trial also provide evidence that biogas digestate can be used as an alternative fertility source for low-nutrient requirement crops and in organic production systems where availability of N for grain fill is often limited. Grain yields from digestate were higher or equal to those achieved with the commercial mineral N fertiliser, which allows for the use of recycled waste-based fertiliser inputs without a drop in productivity and an economic benefit to farmers.

While the results from this trial are encouraging, the commercial development and use of spelt and biogas digestate fertiliser will require improved accessibility to processing facilities. For spelt, de-hulling is an additional step required prior to milling, which is limited to a few millers and grain storage facilities in the UK currently. Applying biogas digestate fertiliser is limited by the lack of widespread anaerobic digestion plants in the UK, which makes transportation and application costs high for most farmers, although the number of facilities is growing annually, with more than 400 digesters currently (NNFCC, 2018).

Regardless of these limitations, interest in spelt as an alternative grain crop continues to grow and the field trial results support the use of milling-quality spelt varieties in arable rotations in the UK.

CHAPTER 4. RYE

Evaluating organic fertilisers and their impact on yield and quality of rye

4.1 INTRODUCTION

Rye (*Secale cereale*) is a tall-growing cereal, cover crop and forage crop. Less effort has gone into developing rye compared to most other cereal species, which has led to fewer rye cultivars available for production (Peltonen-Sainio *et al.*, 2009), although rye is second only to wheat globally as the grain most commonly used in bread production (Bushuk, 2001).

Rye was first cultivated in Europe, with modern areas of greatest concentration in Poland, Germany, western Russia, Belarus and Ukraine (Bushuk, 2001). Rye is valued as a low-input crop based on high winter hardiness (Jedel and Salmon, 1994; Webb *et al.*, 1994; Bushuk, 2001), tolerance of poor climatic conditions and low soil fertility (Bushuk, 2001; Deike *et al.*, 2008; Schlegel, 2014), vigorous and extensive root development (Nedzinskienė, 2006; Schlegel, 2014) and allelopathic properties as a cover crop, mulch and main crop (Mwaja *et al.*, 1995; Smith *et al.*, 2011; Schlegel, 2014; Jabran *et al.*, 2015).

Although rye is grown in the UK, it is considered a cereal of minor national importance in relation to other cereals (wheat, barley and oats) because it represents less than 0.2% of the total UK cereal area (McDonald, 1991). UK rye production has grown, with 36,397 ha harvested in 2017; as a comparison, Poland, the primary European rye producer, harvested 873,222 ha in 2017 (FAOSTAT, 2019). However, the UK has also struggled to consistently produce high quality grain, which means British processors continue to import rye from other countries (McDonald, 1991).

Dietary rye fibre appears more effective than that of wheat in improving bowel health (McIntosh *et al.*, 2003) and consumption of whole-grain rye bread can reduce colon cancer risk and lower cholesterol, especially in men in countries with high rye-bread consumption (Gråsten *et al.*, 2000; Leinonen *et al.*, 2000). Consuming whole kernel rye products has also shown anti-diabetic and anti-obesogenic potential (Sandberg *et al.*, 2016). Due to these characteristics, consumer interest in rye continues to grow, especially for wholegrain products.

This chapter evaluates the yield and quality performance of European rye varieties grown in response to fertiliser type and rate in the UK.

4.2 MATERIALS AND METHODS

4.2.1 EXPERIMENTAL DESIGN

The effects of fertiliser type and variety choice on rye yield and quality were assessed in a two-year experimental field trial at Nafferton Farm. The field trial design, management and data collection methods have been described in full detail in Chapter 3 and therefore only differences from those included previously are presented in this Chapter.

4.2.1.1 EXPERIMENTAL LAYOUT

The field trials were located at Nafferton Farm adjacent to the spelt trials described in Chapter 3. Figure 4.2.1 presents one replicate of the experimental design of the trial with rye varieties clearly labelled. The full trial layout is depicted in Figure 3.2.1, including both spelt and rye and the four replicate blocks.

4.2.1.2 AGRONOMIC MANAGEMENT

The factorial experiments included four varieties of rye: Elvi, Elias, Schlaegler (Sch) and Dankowskie Amber (Dank). Elvi is a modern variety first registered by the Plant Breeding Institute in Estonia in 2000. Elias is a modern Austrian variety sourced from Saatzucht Edelhof (Zwettl, Austria). Schlaegler was first registered in 1936 and is an old Austrian variety. Dankowskie is a modern variety bred by the Polish company Danko and registered in 2010. Variety selection was determined by partners within the HealthyMinorCreals project consortium. All varieties used in this trial were open-pollinated types and were sown on 1 October 2014 in the first year and on 5 October 2015 in the second year of the trial (Table 4.2.1). All varieties were sown at 350 seeds/m^2 in both years and kg/ha rates were calculated based on thousand grain weights (Table 4.2.2).

The fertiliser regimes and herbicide applications were the same as described in Chapter 3.

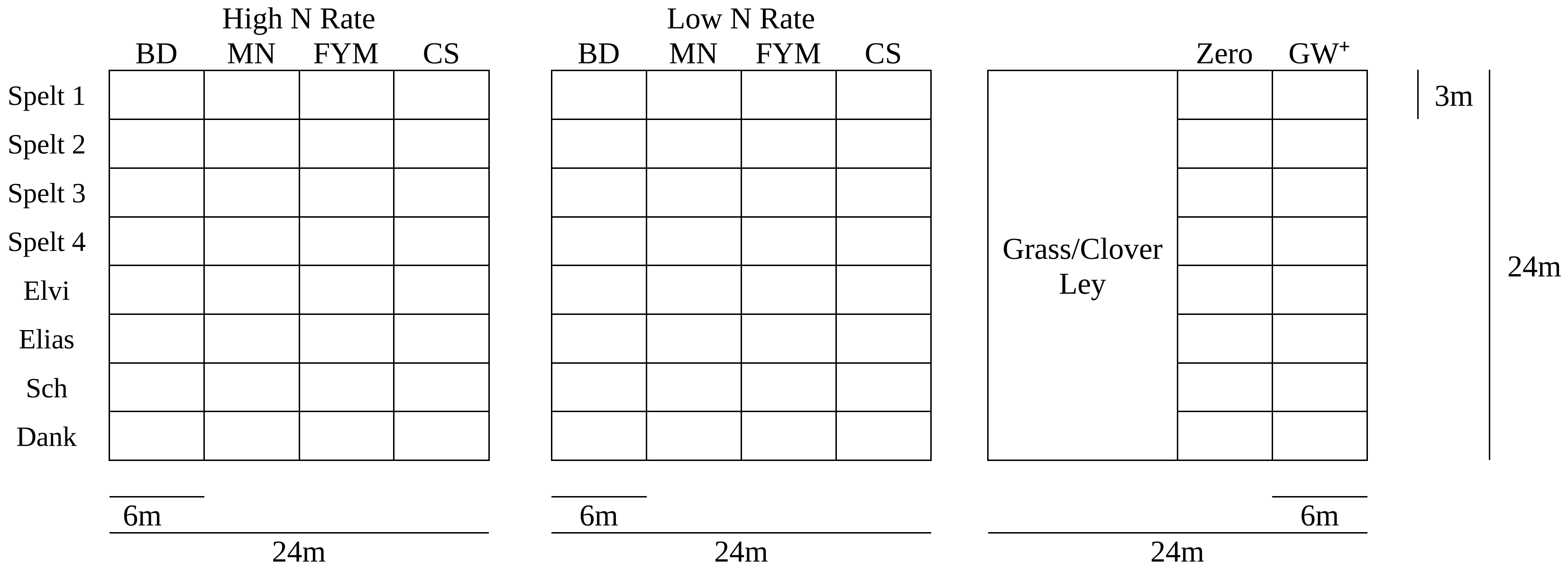

Figure 4.2.1 Field trial design for the rye trials. The layout represents one replicate. The order of fertiliser types and varieties was randomized within each replicate (zero-input treatments were always alongside grass/clover). +Green waste compost (GW) was applied to plots as part of a separate trial—it is included in the experimental design figure to show the full trial layout but further results and discussion from these plots are not included in this thesis.

Table 4.2.1. Crop management details for rye trials in 2015 and 2016.

	2015	**2016**
Previous crop	2 years grass/clover	3 years grass/clover
Sowing date	1 October 2014	5 October 2015
Biomass harvest date	9 September 2015	2-5 September 2016
Combine harvest date	10 September 2015	15-18 September 2016
Herbicide Application Dates		
CleanCrop Gallifrey (*fluroxypyr*)	17 April 2015 (0.6 L/ha)	11 April 2016 (0.35 L/ha)
Isomec Ultra (*dichloroprop-p*)		11 April 2016 (1.5 L/ha)
Fertiliser Application Dates		
Biogas Digestate	16 April 2015	11 May 2016
Cattle Slurry	16 April 2015	11 May 2016
FYM Compost	29 September 2014	22 September 2015
Mineral N	17 April 2015	10 May 2016

Table 4.2.2. Seeding rates (kg/ha) for each rye variety sown in 2015 and 2016.

	2015	**2016**
Elvi	107	105
Elias	157	154
Schlaegler	95	99
Dankowskie Amber	106	113

All varieties were drilled at 350 seeds/m^2 in both years.

4.2.2 EXPERIMENTAL ASSESSMENTS

4.2.2.1 GROWING SEASON ASSESSMENTS

All growing period assessments (leaf disease, leaf chlorophyll content and plant height) were recorded following the methods described in Chapter 3, except that rye leaves were monitored for brow leaf rust (*Puccinia recondita*) and *Septoria secalis* rather than yellow stripe rust (*Puccinia striiformis*) and *Septoria tritici*.

4.2.2.2 GRAIN YIELD ASSESSMENTS

Biomass samples and combine harvest samples were collected following the methods described in Chapter 3. In 2015, rye biomass was collected on 9 September; in 2016, rye biomass was collected from 2-5 September (Table 4.2.1). In 2015, harvest occurred on 10 September; in 2016 crops were harvested 15-18 September (Table 4.2.1).

Combine grain and biomass ear samples were dried, cleaned and threshed at Nafferton farm using a seed cleaner and thresher.

4.2.2.3 YIELD COMPONENT ASSESSMENTS

Yield component assessments were completed following the methods described in Chapter 3; rye does not have a husk, therefore de-hulling was not required for sample processing.

4.2.2.4 GRAIN MILLING QUALITY ASSESSMENTS

Grain milling quality assessments were completed at Coastal Grains Ltd (Belford, Northumberland) following the methods described in Chapter 3, except that rye samples were analysed for specific weight in a DICKEY-john GAC® 2500-UGMA Grain Analysis Computer in 2015 and a FOSS Infratec™1241 Analyzer in 2016.

4.2.2.5 GRAIN NUTRIENT QUALITY ASSESSMENTS

Analyses of nutritional components of grain samples was completed by Sabanci University in Turkey following the methodology described in Chapter 3.

4.2.3 STATISTICAL ANALYSIS

Data analysis was completed following the methodology described in Chapter 3.

4.3 RESULTS

4.3.1 GRAIN HARVEST

4.3.1.1 GRAIN YIELD

Significant main effects of year were detected for rye grain yield ($p = 0.006$); grain yield was significantly higher in 2015 than in 2016 (Table 4.3.1). Highly significant main effects of fertiliser type and variety ($p < 0.001$) were detected for grain yield; biogas digestate and mineral N produced significantly higher yields than all other fertiliser types and Elias was the highest yielding variety (Table 4.3.1).

Significant interaction effects of year and fertiliser type ($p = 0.002$) were detected for rye grain yield (Table 4.3.1); yield differences between input types were not significantly different in 2016 but were significant in 2015 and reflective of main effects (biogas digestate and mineral N fertility resulted in significantly higher yields in 2015) (Table 4.3.2). Highly significant interaction effects of year and variety (p <0.001) were detected for rye grain yield (Table 4.3.1); Elias was the highest yielding variety in both years while Elvi was the lowest yielding in 2015 but Schlaegler was the lowest yielding in 2016 (Table 4.3.3).

4.3.1.2 PLANT HEIGHT

Significant main effects of fertiliser type were detected for rye plant height ($p = 0.015$); farm-yard manure compost produced significantly taller plants than cattle slurry (Table 4.3.1). Highly significant main effects of variety (p <0.001) were detected for plant height; Schlaegler was the tallest and Elvi was the shortest variety (Table 4.3.1).

4.3.1.3 HARVEST INDEX

Highly significant main effects of variety (p <0.001) were detected for rye harvest index; Dankowskie Amber and Elias had significantly higher HI to the other varieties while Schlaegler HI was significantly lower than all other varieties (Table 4.3.1).

Table 4.3.1. Main effect means, ±SE and p-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on rye yield, plant height and harvest index (HI).

	Grain Yield (t/ha)	**Plant Height (cm)**	**HI (%)**
Year			
2015	5.74 ± 0.154	139 ± 1.5	39.0 ± 0.65
2016	3.74 ± 0.096	159 ± 1.6	39.8 ± 0.67
Fertiliser Rate			
0kg N/ha	4.15 ± 0.213	142 ± 3.5	40.1 ± 1.11
50kg N/ha	4.62 ± 0.151	149 ± 1.8	39.4 ± 0.64
100kg N/ha	5.00 ± 0.180	151 ± 1.8	39.2 ± 0.79
Fertiliser Type			
BD	5.27 ± 0.272 a	149 ± 2.5 ab	39.6 ± 0.79
CS	4.53 ± 0.189 b	147 ± 2.6 b	38.5 ± 0.72
FYM	4.23 ± 0.165 b	154 ± 2.8 a	39.0 ± 1.44
M	5.21 ± 0.275 a	149 ± 2.4 ab	39.9 ± 0.94
Variety			
Dank	5.13 ± 0.232 b	142 ± 2.1 c	43.3 ± 0.89 a
Elias	5.59 ± 0.218 a	153 ± 1.6 b	42.9 ± 0.58 a
Elvi	4.22 ± 0.188 c	136 ± 2.5 d	39.6 ± 0.90 b
Sch	4.01 ± 0.168 c	165 ± 2.0 a	31.8 ± 0.61 c
ANOVA *p*-values			
Main Effects			
yr	**0.006**	NS	NS
fr	NS	NS	NS
ft	**<0.001**	**0.015**	NS
var	**<0.001**	**<0.001**	**<0.001**
Interactions			
yr:fr	NS	NS	NS
yr:ft	**0.002**	NS	NS
fr:ft	NS	NS	NS
yr:var	**<0.001**	**<0.001**	NS
fr:var	NS	NS	NS
ft:var	NS	NS	NS
yr:fr:ft	NS	NS	NS
yr:fr:var	NS	NS	NS
yr:ft:var	NS	**0.024**	NS
fr:ft:var	NS	NS	NS
yr:fr:ft:var	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Zero treatments were not included in the ANOVA.

Table 4.3.2. Interaction means ±SE for the effects of year and fertiliser type on rye grain yield.

	Grain Yield (t/ha)			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
2015	6.7 ± 0.38 Aa	5.4 ± 0.25 Ab	4.7 ± 0.21 Ab	6.7 ± 0.33 Aa
2016	3.9 ± 0.19 Ba	3.6 ± 0.18 Ba	3.7 ± 0.23 Ba	3.7 ± 0.23 Ba

Means labelled with the same capital letter within the same column and the same lower case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

Table 4.3.3. Interaction means ±SE for the effects of year and variety on rye grain yield.

	Grain Yield (t/ha)			
	Dankowskie	**Elias**	**Elvi**	**Schlaegler**
2015	6.8 ± 0.30 Aa	7.0 ± 0.27 Aa	4.7 ± 0.32 Ab	5.1 ± 0.21 Ab
2016	3.7 ± 0.17 Bb	4.3 ± 0.19 Ba	3.8 ± 0.24 Bab	3.1 ± 0.16 Bc

Means labelled with the same capital letter within the same column and the same lower case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

4.3.2 YIELD COMPONENTS

Highly significant main effects of year were detected for rye ears/m^2 (p = 0.001) and thousand grain weight (p <0.001), which were significantly higher in 2015 than 2016 (Table 4.3.4). Significant main effects of year were also detected for grains/ear (p = 0.004), although this was significantly higher in 2016 than 2015 (Table 4.3.4). Fertiliser type main effects were highly significant for ears/m^2 (p <0.001) and grains/m^2 (p <0.001); biogas digestate had significantly higher ears/m^2 and biogas digestate and mineral N had significantly higher grains/m^2 than all other fertiliser types (Table 4.3.4). Highly significant main effects of variety (p <0.001) were detected for rye ears/m^2, grains/m^2, grains/ear and TGW; Schaleger TGW was significantly lower than all other varieties (Table 4.3.4).

Highly significant interaction effects of year and variety (p <0.001) were detected for rye ears/m^2 (Table 4.3.4); Elvi had significantly less ears/m^2 in 2015 than all other varieties while Dankowskie Amber had the highest ears/m^2 in both years but the difference was only significant in 2016 (Table 4.3.5).

Table 4.3.4. Main effect means, ±SE and p-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on rye ears/m^2, grains/m^2, grains/ear and thousand grain weight (TGW).

	Ears/m^2	**Grains/m^2**	**Grains/ear**	**TGW (g)**
Year				
2015	286 ± 7.4	10216 ± 297.7	36.0 ± 0.61	49.2 ± 0.30
2016	206 ± 5.5	10095 ± 315.3	49.3 ± 0.89	34.1 ± 0.30
Fertiliser Rate				
0kg N/ha	215 ± 10.5	8881 ± 511.4	42.4 ± 2.12	42.6 ± 1.51
50kg N/ha	256 ± 7.5	10831 ± 331.4	43.5 ± 1.11	41.5 ± 0.69
100kg N/ha	243 ± 8.4	9798 ± 323.6	41.8 ± 0.87	41.6 ± 0.79
Fertiliser Type				
BD	283 ± 14.0 a	11582 ± 518.8 a	42.3 ± 1.18	41.3 ± 1.03
CS	239 ± 10.1 b	9698 ± 428.6 b	42.3 ± 1.60	41.8 ± 0.99
FYM	227 ± 7.9 b	9100 ± 356.9 b	41.4 ± 1.43	41.7 ± 1.07
M	250 ± 11.3 b	10878 ± 491.7 a	44.6 ± 1.39	41.5 ± 1.09
Variety				
Dank	284 ± 10.4 a	11030 ± 385.5 a	40.1 ± 1.09 b	42.7 ± 0.89 a
Elias	249 ± 11.1 b	11091 ± 431.0 a	46.7 ± 1.41 a	43.0 ± 0.95 a
Elvi	210 ± 8.7 c	9618 ± 468.4 b	45.0 ± 1.02 a	42.5 ± 1.11 a
Sch	240 ± 9.5 b	8881 ± 392.4 b	38.6 ± 1.54 b	38.4 ± 0.89 b
ANOVA *p*-values				
Main Effects				
yr	**0.010**	NS	**0.004**	**<0.001**
fr	NS	NS	NS	NS
ft	**<0.001**	**<0.001**	NS	NS
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	**0.020**	**0.014**	NS	**0.038**
yr:ft	**0.050**	NS	NS	NS
fr:ft	NS	NS	NS	NS
yr:var	**<0.001**	**0.025**	**<0.001**	NS
fr:var	NS	NS	NS	**0.004**
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	NS	NS
yr:fr:var	NS	NS	NS	NS
yr:ft:var	NS	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Zero treatments were not included in the ANOVAs.

Table 4.3.5. Interaction means ±SE for the effects of year and variety on rye ears/m^2.

	Ears/m^2			
	Dankowskie Amber	**Elias**	**Elvi**	**Schlaegler**
2015	338.9 ± 13.89 Aa	321.8 ± 13.45 Aa	223.9 ± 15.88 Ac	286.2 ± 12.92 Ab
2016	235.0 ± 12.08 Ba	186.9 ± 11.47 Bb	204.8 ± 10.29 Ab	200.1 ± 12.42 Bb

Means labelled with the same capital letter within the same column and the same lower case letter within the same row are not significantly different (Tukey's Honestly significant Difference test $p < 0.05$).

4.3.3 GERMINATION

Germination % was higher in 2015 than 2016 but this difference was not significant (Table 4.3.6). Highly significant main effects of variety were detected for germination % ($p < 0.001$); Dankowskie Amber and Elias had significantly higher germination % while Elvi germination was significantly lower than all other varieties (Table 4.3.6).

A highly significant interaction effects of year and variety were detected for rye germination % ($p < 0.001$) (Table 4.3.6); Dankowskie Amber, Elias and Schlaegler had significantly lower germination % in 2016 compared with 2015 while Elvi had significantly lower germination % in 2015 compared with 2016. Elvi had significantly lower germination % in 2015 while Schlaegler had significantly lower % germination compared with all other varieties in 2016 (Table 4.3.7).

Table 4.3.6. Main effect means, ±SE and *p*-values for the effects and interactions of year and variety on rye germination percentage of seeds sown in the 2015-2016 trial.

	Percentage
Year	
2015	46 ± 1.7
2016	42 ± 1.6
Variety	
Dank	51 ± 1.5 a
Elias	52 ± 1.4 a
Elvi	30 ± 2.7 c
Sch	45 ± 2.2 b
ANOVA *p*-values	
Main Effects	
yr	NS
var	**<0.001**
Interactions	
yr:var	**<0.001**

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Not all fertiliser types were applied at the time of germination counts and were therefore not included in this assessment.

Table 4.3.7. Interaction means ±SE for the effects of year and variety on rye germination.

	Germination of Seeds Sown (%)			
	Dankowskie Amber	**Elias**	**Elvi**	**Schlaegler**
2015	54 ± 1.6 Aa	56 ± 1.4 Aa	22 ± 1.3 Bb	52 ± 1.4 Aa
2016	46 ± 2.4 Ba	45 ± 1.6 Ba	45 ± 4.3 Aa	32 ± 2.6 Bb

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test $p < 0.05$).

4.3.4 SPAD

Significant main effects of year were detected for SPAD readings at GS59 ($p = 0.018$) and GS69 ($p = 0.008$), which were both significantly higher in 2016 than 2015 (Table 4.3.8). At all three growth stages, highly significant main effects of fertiliser type ($p < 0.001$) were detected; biogas digestate and mineral N had significantly higher readings than the other fertiliser types (Table 4.3.8). Highly significant main effects of variety ($p < 0.001$) were detected for SPAD readings at all growth stages; Elvi had the highest readings at all growth stages, which were significantly higher than all other varieties at GS69 (Table 4.3.8).

Significant interaction effects of year and fertiliser type were detected for rye SPAD readings at GS39 ($p < 0.001$) and at GS59 ($p = 0.012$) (Table 4.3.8); biogas digestate and mineral N had significantly higher SPAD readings at GS39 and GS59 than all other fertiliser types in 2015 but differences between fertiliser types were not significant (excepting biogas digestate and composted FYM) in 2016 (Table 4.3.9 & Table 4.3.10).

Table 4.3.8. Main effect means, ±SE and p-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on rye SPAD readings at three growth stages.

	GS39	**GS59**	**GS69**
Year			
2015	37.9 ± 0.29	36.9 ± 0.37	31.2 ± 0.44
2016	36.9 ± 0.23	41.0 ± 0.35	41.0 ± 0.48
Fertiliser Rate			
0kg N/ha	36.2 ± 0.60	37.3 ± 1.05	34.6 ± 1.63
50kg N/ha	37.5 ± 0.25	38.8 ± 0.40	35.8 ± 0.65
100kg N/ha	37.6 ± 0.30	39.5 ± 0.40	36.7 ± 0.61
Fertiliser Type			
BD	38.8 ± 0.40 a	40.9 ± 0.41 a	38.0 ± 0.74 a
CS	37.5 ± 0.29 b	38.3 ± 0.56 b	35.5 ± 0.97 b
FYM	35.5 ± 0.35 c	36.8 ± 0.67 b	33.5 ± 1.02 b
M	38.5 ± 0.37 ab	40.5 ± 0.45 a	38.0 ± 0.67 a
Variety			
Dank	36.9 ± 0.38 b	37.7 ± 0.53 b	35.2 ± 0.87 b
Elias	37.8 ± 0.39 a	39.3 ± 0.62 a	35.2 ± 0.98 b
Elvi	38.1 ± 0.34 a	40.0 ± 0.50 a	38.0 ± 0.70 a
Sch	36.9 ± 0.38 b	38.8 ± 0.56 a	35.9 ± 0.90 b
ANOVA *p*-values			
Main Effects			
yr	NS	**0.018**	**0.008**
fr	NS	NS	NS
ft	**<0.001**	**<0.001**	**<0.001**
var	**<0.001**	**<0.001**	**<0.001**
Interactions			
yr:fr	NS	NS	NS
yr:ft	**<0.001**	**0.012**	NS
fr:ft	NS	NS	NS
yr:var	**0.031**	**<0.001**	**<0.001**
fr:var	NS	NS	NS
ft:var	**<0.001**	NS	NS
yr:fr:ft	NS	NS	NS
yr:fr:var	NS	NS	NS
yr:ft:var	NS	NS	NS
fr:ft:var	NS	NS	NS
yr:fr:ft:var	**0.028**	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

Table 4.3.9. Interaction means ±SE for the effects of year and fertiliser type on rye SPAD readings at GS39.

	SPAD Readings GS39			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
2015	40.6 ± 0.40 Aa	37.9 ± 0.36 Ab	34.4 ± 0.43 Bc	40.4 ± 0.30 Aa
2016	37.0 ± 0.53 Ba	37.1 ± 0.45 Aa	36.7 ± 0.49 Aa	36.6 ± 0.49 Ba

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

Table 4.3.10. Interaction means ±SE for the effects of year and fertiliser type on rye SPAD meter readings at GS59.

	SPAD Readings GS59			
	Biogas Digestate	**Cattle Slurry**	**Composted FYM**	**Mineral N**
2015	39.5 ± 0.54 Bb	35.9 ± 0.63 Bc	33.6 ± 0.66 Bd	40.1 ± 0.53 Aab
2016	42.3 ± 0.53 Aa	40.7 ± 0.71 Aab	40.0 ± 0.88 Ab	40.9 ± 0.72 Aab

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

4.3.5 DISEASE SEVERITY

4.3.5.1 BROWN RUST

Significant main effects of year were detected for brown leaf rust (*Puccinia recondita*) AUDPC on L3 (p = *0*.036) and L4 (p = *0*.010); disease severity was significantly higher in 2016 than 2015 (Table 4.3.11). Significant main effects of fertiliser type were detected for brown rust AUDPC on L3 (p = *0*.003) and L4 (p <0.001); in response to mineral N, brown rust severity was significantly higher on both leaves than all other fertiliser types (Table 4.3.11). Highly significant main effects of variety (p <0.001) were detected for brown rust AUDPC on all four leaves; Elvi had significantly higher brown rust severity on all four leaves compared to all other varieties (Table 4.3.11).

4.3.5.2 LEAF BLOTCH

Significant main effects of year were detected for leaf blotch (*Septoria secalis)* AUDPC on L1 (p = *0*.025), L2 (p = *0*.010), L3 (p = *0*.014) and L4 (p = *0*.012); leaf blotch disease severity was significantly higher in 2016 than 2015 (Table 4.3.12). Significant main effects of fertiliser type were detected for leaf blotch on L2 (p = *0*.013) and L3 (p = *0*.012); FYM compost had the highest disease severity on both leaves, which was significantly different from biogas digestate and mineral N on L2 and significantly different from mineral N on L3 (Table 4.3.12). Highly significant main effects of variety (*p* <0.001) were detected for leaf blotch AUDPC on all four leaves; disease severity was significantly higher for the varieties Elvi and Schlaegler on L2 and L3 (Table 4.3.12).

4.3.5.3 POWDERY MILDEW

Significant main effects of year were detected for powdery mildew (*Blumeria graminis* f. sp. *Secalis*) AUDPC on L4 ($p = 0.032$); powdery mildew disease severity was significantly higher in 2016 than 2015 (Table 4.3.13). Highly significant main effects of fertiliser type (*p* <0.001) were detected for powdery mildew on all four leaves; biogas digestate and mineral N produced higher powdery mildew disease severity on all four leaves compared with the other fertiliser types (Table 4.3.13). Highly significant main effects of variety (*p* <0.001) were detected for powdery mildew AUDPC on all four leaves; powdery mildew disease severity was significantly higher for the variety Elvi than all other varieties (Table 4.3.13).

Table 4.3.11. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for brown leaf rust (*Puccinia recondita*) on rye leaves.

	Leaf 1	**Leaf 2**	**Leaf 3**	**Leaf 4**
Year				
2015	14.2 ± 2.30	29.6 ± 3.50	25.7 ± 3.13	16.8 ± 2.42
2016	14.8 ± 1.64	29.8 ± 2.81	46.7 ± 3.99	53.9 ± 5.96
Fertiliser Rate				
0kg N/ha	9.7 ± 2.56	20.0 ± 4.84	30.0 ± 6.05	36.7 ± 7.35
50kg N/ha	14.9 ± 2.08	32.4 ± 3.45	41.6 ± 4.52	39.7 ± 6.07
100kg N/ha	15.3 ± 2.31	29.4 ± 3.46	32.4 ± 3.39	30.6 ± 4.24
Fertiliser Type				
BD	16.9 ± 3.51	34.2 ± 5.47	35.0 ± 4.39 b	31.8 ± 5.88 b
CS	12.0 ± 2.35	25.8 ± 3.70	30.5 ± 4.46 b	29.9 ± 5.82 b
FYM	13.8 ± 2.78	27.6 ± 5.03	31.5 ± 5.55 b	20.4 ± 3.80 b
M	17.7 ± 3.61	36.0 ± 5.12	51.0 ± 7.45 a	58.5 ± 11.26 a
Variety				
Dank	3.2 ± 0.54 c	7.1 ± 1.33 c	12.1 ± 2.67 c	18.5 ± 5.56 c
Elias	4.0 ± 1.15 c	9.1 ± 1.85 c	14.1 ± 3.01 c	12.8 ± 3.95 c
Elvi	39.1 ± 4.06 a	69.5 ± 5.29 a	76.3 ± 5.50 a	69.5 ± 6.79 a
Sch	11.7 ± 1.45 b	33.1 ± 3.51 b	42.4 ± 5.00 b	40.6 ± 8.08 b
ANOVA *p*-values				
Main Effects				
yr	NS	NS	**0.036**	**0.010**
fr	NS	NS	NS	NS
ft	NS	NS	**0.003**	**<0.001**
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	**0.048**	NS	NS	NS
yr:ft	NS	NS	NS	**0.003**
fr:ft	NS	NS	NS	NS
yr:var	**0.005**	**<0.001**	NS	NS
fr:var	NS	NS	NS	NS
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	**0.008**	NS
yr:fr:var	NS	NS	NS	NS
yr:ft:var	**0.001**	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Zero treatments were not included in the ANOVAs.

Table 4.3.12. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for leaf blotch (*Septoria secalis)* on rye leaves.

	Leaf 1	**Leaf 2**	**Leaf 3**	**Leaf 4**
Year				
2015	0.00 ± 0.000	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00
2016	6.25 ± 0.582	15.3 ± 1.14	28.3 ± 1.96	15.7 ± 1.74
Fertiliser Rate				
0kg N/ha	2.07 ± 0.829	8.3 ± 2.43	21.5 ± 4.71	11.8 ± 3.82
50kg N/ha	2.60 ± 0.405	8.1 ± 1.13	14.1 ± 1.74	6.2 ± 1.26
100kg N/ha	3.91 ± 0.622	7.0 ± 1.02	12.5 ± 1.97	8.5 ± 1.55
Fertiliser Type				
BD	3.73 ± 0.930	5.9 ± 1.20 b	12.1 ± 2.14 ab	8.2 ± 1.91
CS	3.17 ± 0.688	8.1 ± 1.65 ab	14.1 ± 2.89 ab	8.2 ± 2.37
FYM	3.50 ± 0.733	11.0 ± 1.91 a	17.5 ± 3.28 a	4.1 ± 1.34
M	2.64 ± 0.601	5.4 ± 1.11 b	9.4 ± 1.94 b	9.0 ± 2.20
Variety				
Dank	3.19 ± 0.719 ab	6.0 ± 1.19 b	9.2 ± 2.05 b	4.8 ± 1.53 c
Elias	1.95 ± 0.481 b	4.6 ± 1.19 b	10.7 ± 1.97 b	5.0 ± 1.85 bc
Elvi	4.34 ± 0.853 a	10.4 ± 1.77 a	16.3 ± 2.76 a	9.2 ± 1.93 ab
Sch	3.03 ± 0.630 ab	9.6 ± 1.49 a	20.5 ± 3.15 a	12.5 ± 2.37 a
ANOVA *p*-values				
Main Effects				
yr	**0.025**	**0.010**	**0.014**	**0.012**
fr	NS	NS	NS	NS
ft	NS	**0.013**	**0.012**	NS
var	**0.020**	**<0.001**	**<0.001**	**0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	NS	**0.013**	**0.012**	NS
fr:ft	NS	NS	**0.050**	NS
yr:var	**0.020**	**<0.001**	**<0.001**	**0.001**
fr:var	NS	NS	NS	NS
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	**0.050**	NS
yr:fr:var	NS	NS	NS	NS
yr:ft:var	NS	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

Table 4.3.13. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for powdery mildew (*Blumeria graminis* f. sp. *Secalis*) on rye leaves.

	Leaf 1	**Leaf 2**	**Leaf 3**	**Leaf 4**
Year				
2015	28.7 ± 1.72	53.0 ± 2.60	38.3 ± 2.94	14.8 ± 2.08
2016	26.4 ± 1.77	47.3 ± 2.62	53.4 ± 3.04	30.9 ± 3.10
Fertiliser Rate				
0kg N/ha	18.1 ± 2.62	29.6 ± 3.57	24.6 ± 4.06	10.9 ± 2.61
50kg N/ha	26.9 ± 1.63	48.7 ± 2.32	41.2 ± 2.50	21.4 ± 2.79
100kg N/ha	30.4 ± 2.10	56.7 ± 3.17	55.8 ± 3.82	27.3 ± 3.19
Fertiliser Type				
BD	36.0 ± 2.85 a	62.7 ± 4.08 a	61.3 ± 4.69 a	36.0 ± 5.77 a
CS	20.2 ± 1.72 c	42.5 ± 3.34 b	35.7 ± 3.15 b	15.3 ± 2.57 b
FYM	26.6 ± 2.32 bc	46.5 ± 3.70 b	39.0 ± 3.87 b	12.3 ± 2.05 b
M	32.1 ± 3.15 ab	59.1 ± 4.17 a	58.1 ± 5.68 a	33.7 ± 4.63 a
Variety				
Dank	27.1 ± 2.01 b	49.1 ± 3.27 b	38.4 ± 3.51 b	14.5 ± 2.46 c
Elias	30.7 ± 2.56 b	56.0 ± 4.08 ab	47.2 ± 4.51 b	25.3 ± 4.35 ab
Elvi	39.5 ± 2.71 a	59.7 ± 3.88 a	59.5 ± 4.61 a	34.4 ± 4.13 a
Sch	12.9 ± 1.21 c	35.8 ± 2.88 c	38.3 ± 4.12 b	17.1 ± 3.79 bc
ANOVA *p*-values				
Main Effects				
yr	NS	NS	NS	**0.032**
fr	NS	NS	NS	NS
ft	**<0.001**	**0.001**	**<0.001**	**<0.001**
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	NS	NS	NS	NS
fr:ft	NS	NS	**0.011**	NS
yr:var	**<0.001**	NS	NS	NS
fr:var	**0.007**	NS	**0.016**	**0.034**
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	NS	NS
yr:fr:var	**0.037**	NS	NS	NS
yr:ft:var	NS	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

4.3.6 GRAIN MILLING QUALITY

4.3.6.1 SPECIFIC WEIGHT

Significant main effects of year ($p = 0.003$) were detected for specific weight; rye specific weight was higher in 2015 than 2016 (Table 4.3.14). Highly significant main effects of variety ($p < 0.001$) were also detected; specific weight was significantly higher than all other varieties for Elias and significantly lower than all other varieties for Schlaegler (Table 4.3.14).

Highly significant interaction effects of year and variety were detected for specific weight ($p < 0.001$) (Table 4.3.14); Elias specific weight was significantly higher than all other varieties in both years while Elvi and Schlaegler had the lowest specific weight in 2015 and Schlaegler specific weight was significantly lower than all other varieties in 2016 (Table 4.3.15).

4.3.6.2 PROTEIN CONTENT

Significant main effects of year ($p = 0.002$) were detected for protein content; grain protein was much higher in 2016 than 2015 (Table 4.3.14). Highly significant main effects of fertiliser type and variety ($p < 0.001$) were detected for protein content; mineral N protein was the highest across all fertiliser types, though biogas digestate was not significantly different and Schlaegler had the highest protein levels while Elias protein was significantly lower than for all other varieties (Table 4.3.14).

4.3.6.3 HAGBERG FALLING NUMBER

Highly significant main effects of year and variety ($p < 0.001$) were detected for Hagberg Falling Number; HFN was higher in 2015 than 2016 and Elias had the highest HFNs while Elvi HFN was significantly lower than all other varieties (Table 4.3.14).

Highly significant interaction effects of year and variety were detected for HFN ($p < 0.001$) (Table 4.3.14); Elias HFN was significantly higher than all other varieties in both years while Elvi had the lowest HFN in 2015 and Schlaegler HFN was significantly lower than all other varieties in 2016 (Table 4.3.16).

Table 4.3.14. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on the specific weight, protein content and Hagberg Falling Number (HFN) of rye grain.

	Specific Weight (kg/hl)	**Protein (%)**	**HFN (s)**
Year			
2015	70.4 ± 0.17	7.58 ± 0.076	117.6 ± 3.59
2016	68.3 ± 0.19	11.29 ± 0.119	79.2 ± 1.74
Fertiliser Rate			
0kg N/ha	69.3 ± 0.52	9.38 ± 0.384	NA
50kg N/ha	69.3 ± 0.21	9.35 ± 0.211	NA
100kg N/ha	69.3 ± 0.21	9.49 ± 0.181	98.4 ± 2.62
Fertiliser Type			
BD	69.3 ± 0.28	9.54 ± 0.267 ab	97.5 ± 5.63
CS	69.3 ± 0.28	9.34 ± 0.285 bc	99.1 ± 5.11
FYM	69.4 ± 0.31	9.00 ± 0.259 c	102.0 ± 5.05
M	69.3 ± 0.30	9.81 ± 0.298 a	95.2 ± 5.30
Variety			
Dank	70.4 ± 0.18 b	9.14 ± 0.248 c	97.5 ± 3.73 b
Elias	71.3 ± 0.15 a	8.77 ± 0.234 d	126.6 ± 6.17 a
Elvi	68.7 ± 0.18 c	9.45 ± 0.223 b	79.5 ± 1.55 d
Sch	66.9 ± 0.28 d	10.30 ± 0.302 a	90.2 ± 4.28 c
ANOVA *p*-values			
Main Effects			
yr	**0.003**	**0.002**	**<0.001**
fr	NS	NS	*NA*
ft	NS	**<0.001**	NS
var	**<0.001**	**<0.001**	**<0.001**
Interactions			
yr:fr	NS	NS	*NA*
yr:ft	NS	**0.041**	NS
fr:ft	NS	NS	*NA*
yr:var	**<0.001**	**<0.001**	**<0.001**
fr:var	NS	NS	*NA*
ft:var	NS	NS	NS
yr:fr:ft	NS	NS	*NA*
yr:fr:var	NS	**0.002**	*NA*
yr:ft:var	NS	NS	NS
fr:ft:var	NS	NS	*NA*
yr:fr:ft:var	NS	NS	*NA*

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs. HFN was not analysed for Low or Zero rate fertiliser, therefore the results of a three-way ANOVA are presented here (yrxftxvar).

Table 4.3.15. Interaction means ±SE for the effects of year and variety on rye specific weight.

	Specific Weight (kg/hl)			
	Dankowskie Amber	**Elias**	**Elvi**	**Schlaegler**
2015	71.6 ± 0.11 Ab	72.3 ± 0.12 Aa	68.7 ± 0.28 Ac	68.8 ± 0.21 Ac
2016	69.2 ± 0.15 Bb	70.2 ± 0.13 Ba	68.8 ± 0.18 Ab	65.0 ± 0.25 Bc

Means labelled with the same capital letter within the same column and the same lower case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

Table 4.3.16. Interaction means ±SE for the effects of year and variety on rye Hagberg Falling Number.

	Hagberg Falling Number (s)			
	Dankowskie Amber	**Elias**	**Elvi**	**Schlaegler**
2015	117.4 ± 1.67 Ab	157.2 ± 4.23 Aa	84.2 ± 2.30 Ac	111.7 ± 3.13 Ab
2016	77.6 ± 1.45 Bb	96.1 ± 3.87 Ba	74.7 ± 1.26 Bb	68.6 ± 2.00 Bc

Means labelled with the same capital letter within the same column and the same lower case letter within the same row are not significantly different (Tukey's Honestly significant Difference test p <0.05).

4.3.7 GRAIN NUTRIENT QUALITY

4.3.7.1 MICRONUTRIENT QUALITY

Significant main effects of year were detected for calcium (p = 0.005), copper (p = 0.002), manganese (p = 0.005) and zinc (p = 0.004) and highly significant main effects of year were detected for iron (p <0.001); all micronutrient quantities were significantly higher in 2016 than 2015 (Table 4.3.17). Significant main effects of fertiliser type were detected for calcium (p = 0.003), copper (p <0.001) and manganese (p = 0.002); mineral N had significantly lower copper levels than other input types, FYM compost had significantly lower calcium than other inputs and biogas digestate had significantly lower amounts of manganese than other input types (Table 4.3.17). Highly significant main effects of variety (p <0.001) were detected for all measured micronutrients; Elvi had significantly higher concentrations of calcium and copper, Elvi and Schlaegler had significantly higher concentrations of iron and zinc and Schlaegler had significantly higher concentrations of manganese (Table 4.3.17).

4.3.7.2 MACRONUTRIENT QUALITY

Significant main effects of year were detected for magnesium (p = 0.019) and sulphur (p = 0.003); both macronutrient quantities were significantly higher in 2016 than in 2015 (Table 4.3.18). Significant main effects of fertiliser type were detected for phosphorus (p = 0.008), which was significantly lower in samples fertilised with mineral N (Table 4.3.18). Highly significant main effects of variety (p <0.001) were detected for magnesium, phosphorus and sulphur and significant main effects of variety were detected for potassium (*p = 0*.049); Elvi and Schlaegler had significantly higher concentrations of magnesium and sulphur, Schlaegler had significantly higher concentrations of phosphorus and Dankowksie Amber had significantly lower potassium content than other varieties except Elias (Table 4.3.18).

4.3.7.3 TOTAL PHENOLIC CONTENT

Highly significant main effects of year and variety were detected for total phenolic content in rye grain ($p < 0.001$); TPC was significantly higher in 2016 than 2015 and Schlaegler had significantly higher TPC while Dankowskie Amber had significantly lower TPC than all other varieties (Table 4.3.19).

Highly significant interaction effects of year and variety were detected for TPC ($p < 0.001$) (Table 4.3.19); Schlaegler and Elvi had significantly higher TPC in 2015 while Schlaegler had significantly higher and Dankowskie Amber had significantly lower TPC than other varieties in 2016 (Table 4.3.20).

Table 4.3.17. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on micronutrient content (mg/kg) of rye grain.

	Ca	**Cu**	**Fe**	**Mn**	**Zn**
Year					
2015	315 ± 2.7	3.21 ± 0.043	25.0 ± 0.43	17.4 ± 0.23	23.3 ± 0.35
2016	369 ± 2.1	4.73 ± 0.035	39.4 ± 0.59	21.0 ± 0.22	33.3 ± 0.39
Fertiliser Rate					
0kg N/ha	339 ± 8.1	3.93 ± 0.150	32.6 ± 1.60	18.7 ± 0.39	29.7 ± 1.08
50kg N/ha	341 ± 3.4	3.96 ± 0.081	31.8 ± 0.79	19.8 ± 0.29	28.6 ± 0.64
100kg N/ha	343 ± 3.6	3.97 ± 0.078	32.2 ± 0.90	18.7 ± 0.30	27.5 ± 0.54
Fertiliser Type					
BD	347 ± 5.0 a	4.04 ± 0.110 a	33.0 ± 1.42	18.4 ± 0.37 b	27.7 ± 0.85
CS	346 ± 5.1 a	4.00 ± 0.119 a	31.8 ± 1.12	19.3 ± 0.47 a	28.4 ± 0.86
FYM	343 ± 5.0 a	3.76 ± 0.109 b	31.0 ± 0.98	19.6 ± 0.37 a	27.7 ± 0.74
M	332 ± 4.5 b	4.06 ± 0.112 a	32.3 ± 1.23	19.7 ± 0.45 a	28.2 ± 0.93
Variety					
Dank	328 ± 3.2 c	3.70 ± 0.109 c	30.7 ± 1.41 b	18.2 ± 0.36 c	25.6 ± 0.74 b
Elias	344 ± 4.2 b	3.75 ± 0.108 c	30.4 ± 1.12 b	18.4 ± 0.42 c	25.9 ± 0.72 b
Elvi	366 ± 5.0 a	4.37 ± 0.078 a	33.1 ± 0.62 a	19.3 ± 0.31 b	30.8 ± 0.63 a
Sch	329 ± 4.8 c	4.02 ± 0.107 b	34.1 ± 1.15 a	20.9 ± 0.38 a	30.5 ± 0.84 a
ANOVA *p*-values					
Main Effects					
yr	**0.005**	**0.002**	**<0.001**	**0.005**	**0.004**
fr	NS	NS	NS	NS	NS
ft	**0.003**	**<0.001**	NS	**0.002**	NS
var	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Interactions					
yr:fr	NS	NS	NS	NS	NS
yr:ft	NS	NS	NS	NS	**0.006**
fr:ft	NS	**0.038**	NS	NS	NS
yr:var	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
fr:var	NS	NS	NS	NS	NS
ft:var	**0.021**	NS	NS	NS	NS
yr:fr:ft	NS	NS	NS	NS	NS
yr:fr:var	NS	NS	NS	NS	NS
yr:ft:var	NS	**0.042**	NS	NS	NS
fr:ft:var	NS	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

Table 4.3.18. Main effect means, ±SE and *p*-values for the effects and interactions of year, fertiliser rate, fertiliser type and variety on macronutrient content (mg/g) of rye grain.

	K	Mg	P	S
Year				
2015	4.49 ± 0.018	0.848 ± 0.0045	3.10 ± 0.018	1.00 ± 0.007
2016	4.16 ± 0.054	0.940 ± 0.0126	3.32 ± 0.046	1.26 ± 0.018
Fertiliser Rate				
0kg N/ha	4.37 ± 0.049	0.894 ± 0.0124	3.24 ± 0.048	1.13 ± 0.030
50kg N/ha	4.37 ± 0.042	0.898 ± 0.0099	3.22 ± 0.035	1.14 ± 0.018
100kg N/ha	4.27 ± 0.052	0.890 ± 0.0126	3.19 ± 0.044	1.13 ± 0.019
Fertiliser Type				
BD	4.38 ± 0.029	0.895 ± 0.0099	3.22 ± 0.034 a	1.14 ± 0.021
CS	4.36 ± 0.033	0.908 ± 0.0104	3.30 ± 0.034 a	1.14 ± 0.022
FYM	4.33 ± 0.075	0.900 ± 0.0174	3.25 ± 0.064 a	1.09 ± 0.026
M	4.20 ± 0.101	0.872 ± 0.0226	3.06 ± 0.077 b	1.16 ± 0.034
Variety				
Dank	4.18 ± 0.066 b	0.844 ± 0.0142 b	2.99 ± 0.049 c	1.08 ± 0.025 b
Elias	4.33 ± 0.067 ab	0.868 ± 0.0145 b	3.11 ± 0.050 c	1.08 ± 0.025 b
Elvi	4.41 ± 0.030 a	0.913 ± 0.0081 a	3.28 ± 0.025 b	1.18 ± 0.016 a
Sch	4.37 ± 0.067 a	0.951 ± 0.0165 a	3.46 ± 0.057 a	1.19 ± 0.027 a
ANOVA *p*-values				
Main Effects				
yr	NS	**0.019**	NS	**0.003**
fr	NS	NS	NS	NS
ft	NS	NS	**0.008**	NS
var	**0.049**	**<0.001**	**<0.001**	**<0.001**
Interactions				
yr:fr	NS	NS	NS	NS
yr:ft	NS	NS	NS	NS
fr:ft	NS	NS	NS	NS
yr:var	NS	NS	NS	NS
fr:var	NS	NS	NS	NS
ft:var	NS	NS	NS	NS
yr:fr:ft	NS	NS	NS	**0.048**
yr:fr:var	NS	NS	NS	NS
yr:ft:var	NS	NS	NS	NS
fr:ft:var	NS	NS	NS	NS
yr:fr:ft:var	NS	NS	NS	NS

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Zero treatments were not included in the ANOVAs.

Table 4.3.19. Main effect means, ±SE and *p*-values for the effects and interactions of fertiliser type and variety on total phenolic content (TPC) of rye grain.

	TPC (mg/kg)
Year	
2015	934 ± 12.5
2016	1841 ± 22.1
Fertiliser Type	
BD	1400 ± 89.6
CS	1394 ± 77.5
FYM	1363 ± 83.1
M	1362 ± 93.3
Variety	
Dank	1284 ± 79.9 d
Elias	1322 ± 85.1 c
Elvi	1400 ± 78.1 b
Sch	1517 ± 94.4 a
ANOVA *p*-values	
Main Effects	
yr	**<0.001**
ft	NS
var	**<0.001**
Interactions	
yr:ft	NS
yr:var	**0.003**
ft:var	NS
yr:ft:var	0.1204

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test *p* <0.05).

Table 4.3.20. Interaction means ±SE for the effects of year and variety on total phenolic content (TPC) of rye grain.

	TPC (mg/kg)			
	Dankowskie Amber	**Elias**	**Elvi**	**Schlaegler**
2015	850.1 ± 17.86 Bb	880.2 ± 17.07 Bb	976.8 ± 16.29 Ba	1027.6 ± 20.00 Ba
2016	1717.3 ± 31.70 Ac	1792.5 ± 32.26 Ab	1823.8 ± 31.83 Ab	2038.5 ± 36.56 Aa

Means labelled with the same capital letter within the same column and the same lower-case letter within the same row are not significantly different (Tukey's Honestly significant Difference test *p* <0.05).

4.3.8 MULTIVARIATE ANALYSIS

The bi-plot of the RDA (Figure 4.3.1) shows the relationship between weather, fertiliser treatment, variety and yield and quality parameters of rye. Between them, the included drivers explained 51.5%, axis 1 explained 36.2% and axis 2 a further 12.5% of the variation in the dataset. Radiation was identified as the strongest driver ($p = 0.002$) while the varieties Elvi and Schlaegler ($p = 0.002$), composted farm-yard manure at high rate and cattle slurry at low rate applications ($p = 0.002$), composted farm-yard manure at low rate applications ($p = 0.004$) and cattle slurry at high rate applications ($p = 0.034$) were also identified as important drivers.

Radiation, the strongest driver, was between the negative axis 2 and positive axis 1 and grouped closely with thousand grain weight. Biogas digestate and mineral N fertiliser treatments were grouped between both positive axes and associated with powdery mildew incidence. Composted farm-yard manure treatments and low rate cattle slurry were between the negative axes and cattle slurry was closely associated with harvest index. The high rate cattle slurry treatment was closely associated with the positive axis 2 and negative axis 1. Yield was between the positive axis 1 and negative axis 2, though closer to the negative axis 2, and grouped with ears/m^2. The varieties Elias and Dankowskie Amber were grouped together in between both negative axes while Elvi was isolated from all other drivers between both positive axes, though brown rust disease on all leaves also fell between these axes. Schlaegler was also between the positive axes but more closely associated with axis 1 and powdery mildew incidence. Specific weight was closely associated with the negative axis 2 while protein was between the positive axis 2 and negative axis 1 and grouped with leaf blotch incidence.

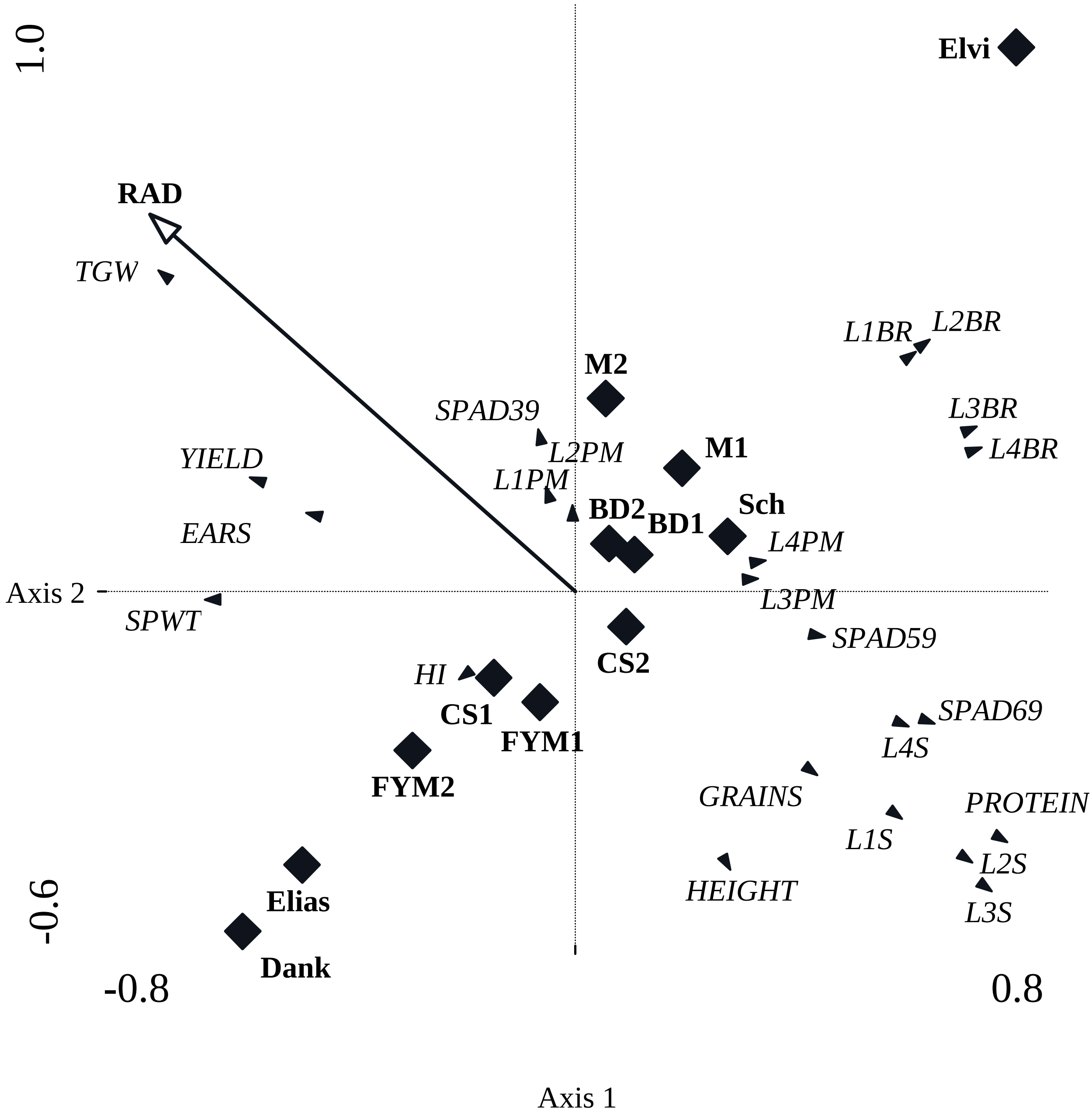

Figure 4.3.1. Bi-plot derived from redundancy analysis showing associations between climatic drivers (RAD—radiation), fertiliser treatments (BD—biogas digestate, CS—cattle slurry, FYM—composted farm-yard manure and M—mineral N at rate 1—50kgN/ha and rate 2—100kgN/ha) and variety (Dank—Dankowskie Amber, Elias, Elvi and Sch—Schlaegler) on yield, plant height (HEIGHT), yield components (EARS—ears/m^2, GRAINS—grains/ear and TGW—thousand grain weight), harvest index (HI), SPAD readings (SPAD39—SPAD at GS39, SPAD59—SPAD at GS59 and SPAD69—SPAD at GS69), disease levels (BR—brown rust, PM—powdery mildew and S—*Septoria secalis* on L1 to L4—leaf 1 to leaf 4) and quality (PROTEIN—protein and SPWT—specific weight) of rye grown in the 2015-2016 field trial.

4.4 DISCUSSION

4.4.1 GRAIN HARVEST

4.4.1.1 GRAIN YIELD

Grain yield was significantly higher in 2015, reflecting overall differences in arable crop production in the UK during the two growing seasons. The year 2015 was exceptionally productive for cereals as wheat yields increased by 4.6% from 2014, resulting in the highest UK average wheat yields in the past 25 years (DEFRA, 2015). Comparatively, UK wheat yields decreased by 12% from 2015 to 2016 (DEFRA, 2016). Annual rye yields are not monitored individually on a national scale in the UK in the same way that the major cereal crops are; instead rye is grouped in with mixed corn and triticale and reported as minor cereals. Regardless, UK minor cereal yields similarly increased from 2014 to 2015 (DEFRA, 2015) and decreased by 28.6% from 2015 to 2016 (DEFRA, 2016). In the trial, rye yield was 35% lower in 2016 (3.74 t/ha) compared to 2015 (5.74 t/ha). Rye benefits from sunny, warm weather with moderate moisture during ripening (Kunkulberga *et al.*, 2017) as cold, rainy conditions during flowering contribute to spikes with empty florets (Bushuk, 1976). Trials in the Netherlands (Hansen *et al.*, 2004) and Poland (Stepień *et al.*, 2016) produced higher rye yields in the warmest trial years and long-term trials in Germany noted that winter rye yields have increased continuously since the 1980s, likely as a result of climate change increasing winter temperatures and creating an earlier growing season (Chmielewski, 1992; Chmielewski and Köhn, 2000). Radiation levels were a major factor contributing to lower yields in the second year, as 2015 had 6% more sunshine hours annually and 34% more sunshine during June in Northeast England compared to 2016 (MetOffice, 2018b). Sunlight absorption is a key contributor to cereal yields, as crop growth and final yields increase with higher radiation absorption, particularly from April through July (Gallagher and Biscoe, 1978). Based on the field station weather data collected at Nafferton farm, total radiation was higher over the full year for 2015 and specifically over April, May, June and July in 2015 (1937 MJ/m^2) compared to 2016 (1342 MJ/m^2) (Table A.1., Appendix A). The RDA bi-plot also identified radiation as the key driver to explain overall variation in the full two-year dataset and contributed to differences in yield and associated parameters, including thousand grain weight. Increased radiation in spring and summer increase cereal yields (Peltonen-Sainio *et al.*, 2010a; Kristensen *et al.*, 2011) and between the two trial years, higher radiation was the main contributor to higher rye yields in 2015 compared to 2016.

Field trials in Europe show that rye yields increase with fertiliser applications (Nedzinskienė, 2006; Gollner *et al.*, 2011; Schlegel, 2014; Stepień *et al.*, 2016), though UK-trials note that lower rates of N are optimal due to the possibility of lodging (McDonald, 1991). Lodging was not a significant factor in either trial year and although yield differences by fertiliser rate were not significantly different, the 100kgN/ha fertility applications produced the highest yields (5.00 t/ha when averaged across both years). Biogas digestate and mineral N produced significantly higher yields (5.27 and 5.21 t/ha respectively) than all other fertiliser input types. Digestate supplies more plant readily available N than other organic fertilisers and animal manures (Tambone *et al.*, 2010; Alburquerque *et al.*, 2012; Möller and Müller, 2012; Wentzel *et al.*, 2015), which was also reflected in significantly higher SPAD readings compared to the composted FYM. The SPAD readings also demonstrate that biogas digestate was similar to mineral N in efficiency of utilisation by the rye crop, resulting in no significant difference between SPAD readings. Coupled with similar results in spelt, the rye results demonstrate the potential of digestate as an alternative organic fertiliser for minor cereals.

Based on interactions, the fertiliser type differences were only significant in 2015, not 2016, indicating that the fertility benefits of higher levels of plant-available nitrogen did not off-set climate-related effects on yield in 2016. The interactions for SPAD readings also show that nitrogen uptake by the rye crop was not significantly different between fertiliser types in 2016, while digestate and mineral N had significantly higher SPAD readings than all other fertiliser types in 2015.

The modern Austrian variety Elias was the highest yielding (5.59 t/ha), while the old Austrian variety Schlaegler and modern Estonian variety Elvi had the lowest yields at 4.01 and 4.22 t/ha respectively. The interaction means show that Elvi produced the lowest yields in 2015 (4.7 t/ha) while Schlaegler had significantly lower yields than all other varieties in 2016 (3.1 t/ha). Elvi is noted as a winter-hardy variety and produces high yields in Estonia (Tupits, 2008), however cultivars that are not adapted to local climatic conditions are outperformed by adapted cultivars, especially in years with non-ideal weather conditions (Hansen *et al.*, 2004). None of the trial cultivars are UK-based varieties and Elvi and Schlaegler seemed particularly ill-suited to the climate of Northeast England.

Although disease severity was mild in comparison to yellow rust in spelt, Elvi had the highest levels of brown rust, leaf blotch and powdery mildew, which likely impacted final yields. The RDA indicated that Elvi was isolated from other factors, including other varieties, and was associated with increased powdery mildew disease incidence. A major contributor to yield differences by cultivar was germination, which was lowest for Elvi in the trial (30%) and significantly lower than all other varieties for Elvi in 2015 (22%) and for Schlaegler in 2016 (32%). Additionally, slug damage was noted in the rye plots over both trial years but was especially evident in the second trial year and in the Schlaegler plots. Although pest incidence was not recorded as an assessment, slugs likely contributed to reduced germination % and low ear numbers in Schlaegler, ultimately resulting in lower yields in 2016.

4.4.1.2 **PLANT HEIGHT**

Rye plant height differences were most evident between varieties, which were all significantly different from each other. The old Austrian genotype, Schlaegler, was the tallest (165cm) while the modern Estonian variety Elvi was the shortest (136cm) and the modern Polish Dankowskie Amber and Austrian Elias had intermediate heights (142cm and 153 cm respectively). Although lodging can be a limiting factor in rye yield, lodging is not necessarily determined by plant height—the amount of precipitation during the growing season has a greater influence than plant height on rye lodging (Peltonen-Sainio *et al.*, 2002; Peltonen-Sainio *et al.*, 2010b), As noted, despite all varieties reaching at least 130cm tall, significant lodging was not present in the field trial, as major precipitation during the growing season, in particular during grain fill, was not a factor.

4.4.1.3 **HARVEST INDEX**

Harvest index is a ratio of final grain yield to total plant biomass and is used as an indicator of reproductive efficiency. In the UK, growers typically aim for a benchmark HI of 50% for winter wheat, indicating that the majority of the crop mass is diverted to the grain (AHDB, 2018b). Due to its much higher straw production from taller stalks, rye harvest index is expected to be lower than wheat.

Overall, the average harvest index for all rye varieties over the two-year trial was 39.4%, which is lower than the benchmark for wheat but not unusual in rye.

There were no significant main effects for year or fertility regimes but significant differences in HI existed between varieties. Cereal breeding techniques for wheat have long selected for shorter stemmed plants to improve harvest index (Pearman *et al.*, 1978; Austin *et al.*, 1980), and the tallest rye genotype, Schlaegler, had a significantly lower HI than all other varieties (31.8%) but the shortest variety, Elvi, did not result in the highest HI (39.6%), instead the intermediate varieties, Dankowskie Amber and Elias, had the highest HI values (43.3% and 42.9% respectively).

4.4.2 YIELD COMPONENTS

Among the yield components for rye, the higher yield in 2015 is reflected in significantly higher ears/ m^2 (286) and TGW (49.2g) compared to 2016 while grains/ear were significantly higher in 2016 (49.3) than 2015. This is also reflected in the RDA, as yield was closely associated with ears/m^2 and related to TGW, which was particularly driven by radiation. Long-term Finnish field trials found that in rye grown in favourable growing conditions, grain yield increased with above average grains/m^2 and TGW (Peltonen-Sainio *et al.*, 2007). The lower ears/m^2 in the second year was also influenced by slug damage, which, as noted previously, was visibly present in 2016. Biogas digestate had significantly higher ears/m^2 (283) than other input types and grains/m^2 were significantly higher for digestate (11582) and mineral N (10878), which is reflected in higher yields for these two fertiliser types.

Schlaegler had a significantly lower TGW (38.4g) than all other varieties while Elvi had significantly lower ears/m^2 (210) than all other genotypes. In a comparison of open pollinated cultivars and hybrid rye, hybrid cultivars had significantly higher TGW than the typical open pollinated varieties (Kunkulberga *et al.*, 2017). Schlaegler is the oldest cultivar included in the trial, without influence of more recent breeding programmes, and the lower TGW reflects that difference in breeding between varieties.

4.4.3 SPAD

SPAD readings to measure cholorphyll content are used as an indicator of leaf N content due to the linear relationship between leaf nitrogen and chlorophyll content in plants (Evans, 1989). While exploring these results can provide additional insight into the effect of different fertiliser regimes on crop production, using a SPAD meter comes with limitations, as discussed in the methodology (Section 3.2.2.1). Although rye SPAD readings were significantly higher in 2016 compared with 2015 at GS39 and GS59, the variation between years is difficult to attribute to a specific factor because chlorophyll content is not uniformetly distributed in plant leaves, which contributes to variation in SPAD meter readings and actual chlorophyll concentration (Parry et al., 2014).

4.4.4 DISEASE SEVERITY

Rye is generally considered less susceptible to leaf disease, especially compared to wheat and barley (Nuttonson, 1958; Bushuk, 1976; McDonald, 1991; Schlegel, 2014), and this is was certainly the case in the field trial. Brown leaf rust (*Puccinia recondita*) and powdery mildew (*Blumeria graminis* f. sp. *Secali*) were the most prevalent diseases in rye over both trial years, but not nearly to the same extent as yellow rust (*Puccinia striiformis*) severity in spelt (Figure 3.2.2).

Leaf blotch (*Septoria secalis*) was also observed in rye but in very small quantities, including no detectable presence in 2015 and an AUDPC less than 30 on all leaves across all varieties and fertiliser types in 2016 (Leaf 3 AUDPC=28.3). Brown rust disease levels were higher on the top three leaves of crops treated with mineral N, and this difference was significant on Leaf 3 (AUDPC=51.0). Disease levels were significantly higher for biogas digestate and mineral N on the top three leaves for powdery mildew—the highest severity occurred on Leaf 2 (digestate AUDPC=62.7; mineral N AUDPC=59.1). Powdery mildew incidence was also closely associated with biogas digestate and mineral N fertility applications in the RDA. As noted, similar results were observed in wheat at Nafferton farm, where powdery mildew disease levels were higher with synthetic N compared with composted FYM fertiliser applications (Bilsborrow *et al.*, 2013; Rempelos *et al*., 2018) and higher disease levels with excessive nitrogen fertilisation has also been observed in rye (Bushuk, 1976).

The effect of high nitrogen application resulting in increased disease severity did not appear to impact final yield by fertiliser type, but variety susceptibility to disease did have a yield impact, especially for Elvi. As noted, Elvi had the highest disease levels of all varieties, including brown rust on Leaf 3 (76.3) and powdery mildew on Leaf 2 (AUDPC=59.7) and, along with Schlaegler, produced the lowest yields in the trial.

While leaf disease is not considered a major problem for rye production, ear diseases can contribute to yield losses and quality deterioration. Fusarium (*F. graminearum*) has been linked to rheological quality in flour by increasing mycotoxins and decreasing falling number (McDonald, 1991) and rye is more sensitive to ergot (*Claviceps purpurea*) parasitisation than other cereals (Schlegel, 2014). Ergot infection in rye is more likely in humid summers (Bushuk, 1976) and ears are particularly susceptible when rainfall occurs at flowering (Miedaner and Geiger, 2015). Significant ear disease was not identified in the rye in either trial year, which were not humid and rain at flowering was not a major concern. This was the first time rye was grown at the field site, which also likely contributed to the lack of ergot presence, but the risk remains for future rye crops.

4.4.5 GRAIN QUALITY

The same milling quality parameters described in Chapter 3 (Table 3.4.1) are also considered for rye quality, although unlike spelt, which follows UK hard wheat specifications, rye does not have a UK-based milling specification. Typically, rye is expected to have a lower specific weight and much lower protein content and Hagberg Falling Number than wheat and because of this, bakers treat it differently than typical wheat flours. Rye is not as effective as wheat for high-volume breads but is instead used to produce much darker and heavier bread (consumed extensively in Germany and Eastern Europe) and is mixed with wheat for 'light-rye' breads (Nuttonson, 1958; Bushuk, 2001). The quality specifications for rye typically accepted by artisan bakers in the UK include a minimum HFN of 110 seconds and specific weight above 72 kg/hl (Table 4.4.1).

Table 4.4.1. Typical Milling Rye Specifications for specific weight, protein content and Hagberg Falling Number (A Wilkinson, pers.comm.).

Specific weight (kg/hl)	72
Protein (%)	7-11
Hagberge Falling Number (s)	110

4.4.5.1 SPECIFIC WEIGHT

Typical minimum specific weight for rye in the UK is 72 kg/hl (Table 3.4.1) and the rye in the trial did not meet this minimum requirement in either year, though 2015 grains had a significantly higher specific weight (70.4 kg/hl) than 2016 (68.3 kg/hl). Harvest year weather conditions impact specific weight—warmer, sunny conditions contribute to higher test weights (Hansen *et al.*, 2004) while rainy summer conditions lead to lower specific weights (Salmenkallio-Marttila and Hovinen, 2005) and although rainfall was not notably higher in 2016, the same increase in radiation in 2015 noted as a factor in higher harvest may have also influenced specific weight differences.

Specific weight was significantly different between varieties. Elias had the highest specific weight (71.3 kg/hl) while Schlaegler had the lowest (66.9 kg/hl). Based on interactions, Dankowskie Amber and Elias met the minimum specification in 2015 (71.6 and 72.3 kg/hl respectively) but not in 2016 (69.2 and 70.2 kg/hl respectively).

4.4.5.2 PROTEIN

Typical minimum protein for rye in the UK is 7-11% (Table 3.4.1) and the rye in the trial fell within this range in both trial years. Similar to spelt, rye protein was significantly higher in 2016 (11.29%) than 2015 (7.58%), which also followed protein content trends in the UK, which were noted to be the highest in ten years for winter wheat in 2016 (AHDB, 2016b).

Similar to spelt, higher plant available N content fertilisers resulted in higher protein levels; mineral N produced significantly higher protein content (9.81%) than all other fertiliser types except for biogas digestate (9.54%), which was expected because grain protein content is calculated based on grain N content (Merrill and Watt, 1955). Field trials in Poland (Stepień *et al.*, 2016) and the United States (Mishra *et al.*, 2017) found that mineral fertilisers increased protein content in rye grain.

All protein content differences by variety were significant and all varieties met the typical minimum protein content specification for rye in the UK. The old, taller Austrian variety Schlaegler had the highest protein content (10.30%) while the modern Austrian variety Elias had the lowest protein content (8.77%).

As noted in Chapter 3, the quality parameters identified by the National Association of British and Irish Flour Millers are designated based on the requirements of industrial bread-making using common wheats. Bakers working with alternative flours and artisanal bread-making methods note that flour quality standards for the Chorleywood Bread Process, which relies on high-energy minerals and chemicals for a quick-rise white bread, do not apply to slow-fermentation bread-making (Whitley, 2009). Rye in particular is noted for having much lower protein content than wheat (Nuttonson, 1958; McDonald, 1991; Kowieska *et al.*, 2011) and bakers who work regularly with rye are not reliant on typical quality metrics but are prepared to use alternative methods to produce different types of bread products, including sourdoughs and mixed-flour breads (Schlegel, 2014).

4.4.5.3 HAGBERG FALLING NUMBER

Typical minimum Hagberg Falling Number for rye in the UK is 110 seconds (Table 3.4.1) and the rye in the field trial met the minimum specification in 2015 (117.6 seconds) but not in 2016 (79.2 seconds). Rye is particularly susceptible to high alpha-amylase activity, as rye grain has a strong tendency to sprout on the ear due to low harvest dormancy (Schlegel, 2014) and in warm, wet climates (Bushuk, 1976). Low HFN contributing to poor grain quality has been the main limitation to increasing rye production in the UK (McDonald, 1991). As is the case for other cereals, wet conditions pre-harvest, especially if heavy rainfall delays harvest, reduces rye HFN (McDonald, 1991; Hansen *et al.*, 2004; Salmenkallio-Marttila and Hovinen, 2005; Tupits, 2008; Kunkulberga *et al.*, 2017) and neither harvest period in the field trials was notably dry.

Differences between fertiliser types were not significant but differences in HFN by variety were significant. Elias was the only variety that met the minimum requirement (126.6 seconds) and was significantly higher than all other varieties while Elvi had a significantly lower HFN than all other varieties (79.5 seconds). Based on interactions, all varieties except one met the typical HFN minimum for rye in 2015; Elias HFN was significantly higher than all other varieties (157.2 seconds) while Elvi HFN was significantly lower than all other varieties (84.2 seconds) in 2015. Hansen *et al.* (2004) note that some varieties are better adapted to maintain reasonable HFN in rainy conditions, but that harvest year has a stronger influence on HFN than cultivar overall. The differences between years indicates that all varieties except Elvi are capable of meeting minimum HFN specifications but that variation in climatic conditions can have a strong impact on grain quality in a given year.

4.4.6 GRAIN NUTRIENT QUALITY

4.4.6.1 **MICRONUTRIENT QUALITY**

As was the case in the spelt trial, rye micronutrient content was significantly higher for all measured nutrients in 2016 than 2015 and within the two-year Nafferton field trial, rye grains produced lower micronutrients than spelt, except for calcium. Although rye has been shown to contain higher zinc concentrations than wheat (Jorhem and Slanina, 2000; Kowieska *et al.*, 2011), rye grains are not noted for having particularly high micronutrient contents compared to other cereals (Kowieska *et al.*, 2011; Rodehutscord *et al.*, 2016).

Variety had highly significant effects on micronutrient quality, with Elvi grain producing the highest concentrations of calcium (366 mg/kg) and copper (4.37 mg/kg), Schlaegler producing the highest concentrations of manganese (20.9 mg/kg) and Elvi and Schlaegler producing significantly higher concentrations of iron (33.1 and 34.1 mg/kg respectively) and zinc (30.8 and 30.5 mg/kg respectively). This shows clear genetic variation for grain nutrient concentrations, which could be a potential target in future breeding programmes.

4.4.6.2 MACRONUTRIENT QUALITY

Over the two-year field trial, rye grains contained higher levels of potassium but less magnesium, phosphorus and sulphur than spelt. Rye has been shown to be higher in potassium but lower in magnesium than other cereals in two European studies (Kowieska *et al.*, 2011; Rodehutscord *et al.*, 2016), but is not considered to be an exceptional source of potassium compared to wheat.

Macronutrient content differences were significant for variety, with Dankowskie Amber producing significantly lower concentrations of potassium (4.18 mg/g), Schlaegler producing significantly higher phosphorus content (3.46 mg/g) and Elvi and Schlaegler producing significantly higher magnesium (0.913 and 0.951 mg/g respectively) and sulphur (1.18 and 1.19 mg/g respectively).

4.4.6.3 TOTAL PHENOLIC CONTENT

Rye has been shown to contain high levels of phenolic compounds (Cukelj *et al.*, 2015; Mishra *et al.*, 2017) and, as is true in other cereals, the majority are contained in the bran (Liukkonen *et al.*, 2003; Heiniö *et al.*, 2008; Bondia-Pons *et al.*, 2009) and ferulic acid is the most abundant (Andreasen *et al.*, 2000; Bondia-Pons *et al.*, 2009). Phenolic compounds in rye are higher than in many other common grains (Liukkonen *et al.*, 2003), including in comparison to wheat (Rybka *et al.*, 1993; Zieliński and Kozłowska, 2000; Ward *et al.*, 2008). Over the full two-year trial, total phenolic compounds were much higher in rye than for spelt, reflecting this overall high phenolic content compared to other cereals.

As was the case in spelt, total phenolic content was significantly higher in 2016 (1841 mg/kg) than 2015 (934 mg/kg). While this difference is not quite as dramatic as the year-to-year TPC difference in the spelt, polyphenols were 97% higher in 2016 compared to 2015. The same yield dilution and potential environmental factors at play in the spelt are relevant to the rye results and as is the case for wheat, variation in rye phenolic content is attributed to both genotype and year-to-year environmental factors (Andreasen *et al.*, 2000).

The rye trial results show highly significant main effects of variety. Schlaegler had significantly higher phenolic content (1517 mg/kg) than all other varieties, followed by Elvi (1400 mg/kg), which was significantly higher than Elias (1322 mg/kg) and Dankowskie Amber (1284 mg/kg). As noted for spelt, plants produce phenolic compounds in response to stress (including disease) (Nicholson and Hammerschmidt, 1992), and Elvi and Schlaegler were the most susceptible to leaf diseases, which may have contributed to higher phenolic concentrations in the grain.

4.5 CONCLUSIONS

Rye is typically grown on the brash drought-prone soils of Southeast England, where it often outperforms wheat and barley under these conditions, but the results provide valuable data about and experience of growing European rye varieties in Northeast England, which can be used to recommend preferred management practices, including variety choice and fertiliser inputs, for rye production.

The more promising varieties from this trial are the modern Polish variety Dankowskie Amber and the Austrian variety Elias. Elias was best-suited to the variable climatic conditions, displayed leaf disease resistance and produced higher yields and higher baking quality grains than other genotypes. Ergot remains a concern for rye production and future trials will benefit from additional analysis to detect ergot post-harvest to identify less susceptible varieties.

The field trial results also provide evidence that biogas digestate can be used as an alternative fertility source for low-input crops and in organic production where N availability for grain fill is often limited. Grain yields from digestate matched those achieved with the commercial mineral N fertiliser, allowing for recycled waste-based fertility applications without productivity losses.

While the trial results are encouraging, there remain major concerns and limitations to the use of rye and biogas digestate fertiliser commercially. Early rye establishment requires attention to sowing dates and slug management to prevent early crop losses and achieving a consistently high Hagberg Falling Number is still a concern in a region which often experiences wet harvest periods. Additionally, applying biogas digestate fertiliser is limited by the lack of widespread anaerobic digestion plants, which makes transportation and application costs high for most farmers, although the number of facilities is growing annually, with more than 400 digesters currently in the UK (NNFCC, 2018).

Despite these limitations, interest in rye as a healthy alternative grain crop continues to grow at a consumer level and the field trial results demonstrate the possibility of milling-quality rye varieties in arable rotations in the UK.

CHAPTER 5. ONLINE DATABASE

Creating and utilising an online participatory data management system

5.1 INTRODUCTION

Following the two-year spelt and rye trials at Nafferton-farm, the same varieties were included in a multi-site Farmer Participatory trial (FPT). Establishing on-farm research included recruiting participant farmers and creating a web-database to facilitate data collection and collaboration between researchers and growers.

Participatory agricultural research supports both the research and industry communities by creating a dialogue between farmers and researchers to address 'real' problems in agriculture and improve the impact of agricultural research (Lockeretz, 1987; Hellin *et al.*, 2008; Neef and Neubert, 2011). On-farm trials aid the farmer decision-making process by providing an opportunity to evaluate new practices (Franzen *et al.*, 2004; Lawes and Bramley, 2012; ADAS, 2018) and allow research to consider a range of conditions, including a range of physical conditions and management practices (Lockeretz, 1987; Rzewnicki *et al.*, 1988).

Farmer participatory trials are often used for cultivar evaluation across multiple sites (Yan *et al.*, 2002; Llewellyn, 2007) and the development of precision agriculture technologies have increased on-farm trials of nutrient management practices (Sylvester-Bradley *et al.*, 2017). Recent agronomic projects encourage farmers to take ownership of their own crop trials by using precision cropping technologies and related electronic data recording tools to assemble comprehensive multi-field and farm data, which is increasingly available through open source frameworks (Sylvester-Bradley *et al.*, 2017; ADAS, 2018).

The earliest computer-based data processing systems designed for agriculture primarily functioned to organise and retrieve data related to plant breeding (Andrews *et al.*, 1978) and were expanded to create computer-based packages within the database that would generate experimental designs and clerical materials associated with field work (Andrews and Hardwick, 1982). While these kinds of systems continue to be used to collect, organise and share genotypic and phenotypic crop data (Fox *et al.*, 1997; WheatIS, 2018), agro-ecological databases grew more ambitious and sophisticated over time. Software technology was used to create a data management system to store and monitor multisite experiments (van Evert *et al.*, 1999) and increased data sharing led to databases for simulation modelling and decision-making support (McCown *et al.*, 1996; Jones *et al.*, 2003; White *et al.*, 2013).

While many of these systems are primarily used by crop breeders and scientists, the growth of internet-use for data collection and improvements in agricultural technology has led to greater numbers of research and development projects focusing on farmer innovation (MacMillan and Benton, 2014). Online systems for knowledge exchange and data management have massive potential in agriculture to benefit on-farm decision-making and experimental research through widespread accessibility (Bostick *et al.*, 2004; Bruce, 2016).

The scope of the spelt and rye FPT included collecting historical farm and experimental field management data as well as crop health, yield and quality assessment measurements for the trial plots. An online database was built to facilitate data input and monitoring as well as collaboration between farmers and researchers for the duration of the spelt and rye trials and for future such participatory research projects.

This chapter describes the production of the online database system for farmer participatory trials and identifies the range of information required and traits recorded throughout the growing season.

5.2 MATERIALS AND METHODS

5.2.1 FARMER PARTICIPATION

Establishing the FPT included contacting farmers in Northeast England to both identify potential participants and receive input on how farmers would prefer to use an online database. This included organising and participating in dissemination events relating to growing alternative cereals.

5.2.1.1 DISSEMINATION EVENTS

Six separate events took place at Nafferton-farm to disseminate information from the Nafferton field trials and the Farmer Participatory trials (Table 5.2.1). Three of these events took place prior to the establishment of the FPT and were used for participant recruitment. All attendees were asked to provide contact details and indicate their interest in future trial updates and/or participating in farm-based spelt and rye trials. Additionally, spelt and rye trial information was distributed at relevant events in Northumberland, including on-farm workshops, trade-shows and producer conferences (Table 5.2.1). Three of the participant farmers were recruited through dissemination events and committed to the project after follow-up from their initial interest in the spelt and rye trials at Nafferton farm.

5.2.1.2 FARMER NETWORK

At the time of recruitment for the FPT, Nafferton farm was affiliated with the Nafferton Ecological Farming Group (NEFG), a Newcastle University research unit focused on low-input and organic approaches to crop and livestock management. NEFG developed a reputation for field trials and research into sustainable agriculture which contributed to interest in the spelt and rye trials and provided contacts for farmer participatory recruitment. The unofficial NEFG farmer network was utilised to promote dissemination events and reach out to partners in other research projects. Four farmer-participants were recruited through NEFG and affiliated projects, including an existing Knowledge Transfer Partnership (KTP) with Coastal Grains Ltd. (Belford, Northumberland).

Table 5.2.1. All events related to dissemination of spelt and rye trial results and Farmer Participatory trial recruitment.

Event	Location	Date	Engagement	Audience
Spelt & Rye Information Session	Nafferton-farm, Stocksfield	July 2015	Recruitment/ Dissemination	Northeast growers, bakers, millers
Spelt & Rye Information Session	Nafferton-farm, Stocksfield	Nov 2015	Recruitment/ Dissemination	Northeast growers, bakers, millers
Northumberland County Show	Stocksfield	May 2016	Dissemination	General Public
SoapBox Science	Newcastle City Centre	June 2016	Dissemination	General Public
Spelt & Rye Information Session	Nafferton-farm, Stocksfield	July 2016	Recruitment/ Dissemination	Northeast growers, bakers, millers
National Organic Combinable Crops	Wimpole Estate, Cambridgeshire	July 2016	Dissemination	Organic growers, bakers, millers, breeders, certifiers
SIP Workshop	Nafferton-farm, Stocksfield	Sept 2016	Dissemination	SIP Stakeholders
Bread and Community Workshop	Nafferton-farm, Stocksfield	Oct 2016	Dissemination	Northeast growers, bakers, millers
SIP Arable Workshop	The Allerton Project, Loddington	Dec 2016	Dissemination	SIP Stakeholders
Coastal Grains KTP Event	Spindlestone Farm, Belford	July 2017	Dissemination	Coastal Grains Members
SIP Workshop	Nafferton-farm, Stocksfield	Oct 2017	Dissemination	SIP Stakeholders
SIP AAB Conference	Rothamsted Research, Harpenden	Nov 2017	Dissemination	SIP Stakeholders/International Conference Attendees
National Organic Combinable Crops	Green Acres Farm, Shropshire	July 2018	Dissemination	Organic growers, bakers, millers, breeders, certifiers
Coastal Grains KTP Event	Fallodon Hall, Alnwick	July 2018	Dissemination	Coastal Grains Members

SIP—Sustainable Intensification research Platform; KTP—Knowledge Transfer Partnership

5.2.2 DATABASE CONTENTS

The International Benchmark Sites Network for Agrotechnology Transfer identified a common set of required information necessary for meaningful agronomic database interpretation, including weather, site description, initial conditions, management, soil data and crop performance (Hunt *et al.*, 2001). These are all included in the database, with specific details relevant to the spelt and rye FPT but also with the capacity to include additional types of data required by future projects.

5.2.2.1 WEATHER DATA

Tracking climatic differences across sites and trial years is valuable to agronomic databases, especially to assist in decision-making (Jones *et al.*, 2003). Weather data was not specifically recorded by participants or researchers for the FPT but local weather station and regional climatic data is available through the UK MetOffice (MetOffice, 2018a). The nearest weather station for each site may vary (in the case of the spelt and rye FPT, most farms were between the Durham and Cockle Park Stations), which requires flexibility. In considering the system design, specific weather inputs were not included, but instead the database has the option for climatic data (rainfall, air temperature and radiation) to be added as a direct input or accessed via the MetOffice.

5.2.2.2 FARM DATA

Farm background data provides metadata for the FPT, including historical farm management practices and specific management practices applied to the experimental field site containing the FPT. Farm background data includes specific location details (post code, GPS coordinates, elevation), farm descriptors (size, type, presence of livestock) and typical management practices (organic/non-organic, rotation, fertiliser treatments, crop protection, tillage). Separate from typical management, experimental field management describes the specific practices that took place in each FPT field, serving as an agronomic diary to record sowing date, fertility, crop protection and/or tillage applications, etc. Collecting relevant farm data provides context for crop performance at specific sites and allows for the evaluation of research-derived techniques that may be sensitive to management skill (Lockeretz, 1987). Details about farm management may be used as factors in data analysis depending on the scale and scope of the FPT using the database.

5.2.2.3 **SOIL DATA**

A key difference between FPT and experimental field trial research is the opportunity to include different soil and physical properties within the dataset (Lockeretz, 1987). Including soil data as part of agro-ecological datasets is particularly valuable to develop a 'cropping systems' approach to on-farm decision-making (McCown *et al.*, 1996; Hunt *et al.*, 2001; Jones *et al.*, 2003). The spelt and rye FPT included winter soil collection for analysis of pH and basic nutrient content (NPK) and organic matter at each site, however the database allows for more detailed soil mineral inputs, including micronutrients, mineral N in early spring and heavy metals concentrations.

5.2.2.4 **CROP HEALTH DATA**

Measuring crop performance includes recording crop health throughout the growing season. The spelt and rye FPT followed the crop health field assessment methodology described in Chapters 3 and 4 to record disease severity and leaf greenness (especially when using different fertiliser treatments), which both impact final crop yield. The database also includes data inputs relating to crop growth, including emergence, key growth stage milestones and early tillering. The potential for weed assessments is also considered, and the database includes functionality to add additional assessments as required by a future project. Any experimental assessment entry includes a 'date' field to allow for multiple recordings of the same assessments at different dates/growth stages. The emphasis on crop agronomy is based on the spelt and rye trial assessments (data presented in Chapter 6), but the database has the potential for use in livestock, horticulture and/or biodiversity related trials in the future.

5.2.2.5 **YIELD AND QUALITY DATA**

The final data inputs of the FPT include grain yield and quality as final crop performance indicators. Following the methodology in Chapters 3 and 4, grain yield included combine grain and biomass harvest parameters while grain quality is based on milling specifications, including protein, specific weight and Hagberg Falling Number. Especially as part of a FPT, yield is a key indicator for participants, reflecting the 'real world' viability of the experimental inputs, who are especially interested economic feasibility (Rzewnicki *et al.*, 1988). Quality parameters also provided some insight into economic viability, as cereals grown to high milling specification have a higher market value (NABIM, 2018). The focus on protein, specific weight and HFN as indicators is based on parameters used for milling specifications by the National Association of British and Irish Millers (NABIM, 2014), however as noted the database can included additional assessment input types based on any future research requirements.

5.2.3 DATABASE CREATION

Data collection and management for the FPT was facilitated by an online database, which was accessible to participant farmers and project researchers. A web-platform was designed specifically for the trial, with scope to be used in future research projects, and was developed with input from University IT specialists and research project supervisors, partners and stakeholders. The website is hosted on the Newcastle University server at https://internal.ncl.ac.uk/safrd/hmcdata/.

5.2.3.1 DATA DICTIONARY

The first step in planning the database was to create a data dictionary, which is a list of all potential inputs, including descriptions, justifications and formatting notes. Establishing a common set of required information, common vocabulary and common file structure is beneficial to agronomic data collection and exchange (Hunt *et al.*, 2001). The first draft of the dictionary was a list of data entry inputs for participant farmers/researchers to satisfy research requirements. The list included farm background information, soil type/analysis data, an agronomic diary, experimental field information and experimental assessment inputs (Table 5.2.2). The data management system was set-up for the FPT as part of the EUFP7 project HealthyMinorCereals, including use by partners in the Czech Republic and Estonia.

After being circulated for feedback to project partners (Czech Republic and Estonia) and updated with inputs requested by farmers who attended dissemination events, the data dictionary was updated into an Excel document with additional information about each data entry, including data type, units and formatting requirements (Table 5.2.3). IT-specialists with experience in web-database creation then reviewed the data dictionary to check for transferability into a MySQL database.

The final data dictionary (Table B.1., Appendix B) served as a reference point for creating the MySQL database tables. Please note that the background data inputs and assessments reflect the specificity of the spelt and rye trials but also allow for additional records for future trials, that is, the dictionary is by no means comprehensive but served as a working document during database construction.

Table 5.2.2. Data input types included in the full data dictionary.

Farm Background	**Farm Management**	**Experimental Field**	**Experimental Assessments**$^{+}$
Geographic Location	*Typical Management*	*Field Background*	*Soil*
Farm Name	Management System	Soil type	pH
Post Code	Crop Rotation Length	Gradient	N
Elevation	Crop Rotation	GPS	P
Farm Description	Fertiliser Type(s)	Orientation	K
Farm Size	Fertiliser Rate(s)	Size	Fe
Farm Type	Fertiliser Timing(s)	Previous Crop	Mn
Livestock Present?	Synthetic Crop Protection?	*Trial Management*	Zn
Livestock Type(s)	Crop protection type(s)	Trial Species	Cu
Stocking Rate(s)	Crop protection rate(s)	Trial Varieties	B
Manure Present?	Crop protection timing(s)	Sowing Date	Hg
Manure Processing	No-Chem Weed control?	Seed Rate	Other Heavy Metals
Additional Details	Weed control type(s)	Fertiliser Type(s)	*Crop Growth*
	Weed control timings	Fertiliser Rate(s)	Emergence
	Tillage system	Fertiliser Timing(s)	Tiller count
	Additional Management	Synthetic Crop Protection?	GS31 Date
		Crop protection type(s)	GS39 Date
		Crop protection rate(s)	GS62 Date
		Crop protection timing(s)	Weed density
		No-Chem Weed control?	Weed composition
		Weed control type(s)	Plant height
		Weed control timings	SPAD
		Tillage	Disease score
			Lodging
			Grain Harvest
			Harvest Date
			Combine Yield
			Sub-sample FW Yield
			Sub-sample DW Yield
			Moisture %
			Biomass Harvest
			Plant Number
			Tiller Number
			Tiller Weight
			Ear Number
			Ear Weight
			1000 grain weight
			Grain Quality
			Specific Weight
			Protein
			Hagberg Falling Number

FW—Fresh Weight; DW—Dry Weight

$^{+}$Experimental assessments will include a date of assessment as many crop growth assessments will be repeated at different dates/growth stages.

The full data dictionary is in Appendix B (Table B.1)

Table 5.2.3. Sample of data dictionary utilised in online data management system planning (full data dictionary Table B.1., Appendix B).									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Farm Background									
Geographic Location									
Farm Name	Name of Farm Business	Reference for trial site	Text	N/A	Full farm name	Once	Farmer		Cell needs to be filled
Post Code	Farm address postcode	Identify farm location	Text	N/A	e.g. NE43 7XD	Once	Farmer	Should fall within county	Empty cells filled manually using farm name
Elevation	Location of farm relative to sea level	Compare between farm elevations	Numeric	m > sea level	Numbers	Once	Researcher		Empty cells filled manually using farm location
Farm Description (General descriptors of participating farm)									
Farm Size	Area of farm site	Size-based comparisons	Numeric	ha	Numbers	Annual	Farmer	Should be at least same size or larger than field size	
Farm Type	E.g. arable, dairy, mixed	Compare between types	Text	N/A	Option to select from list	Annual	Farmer	Mixed/dairy should have livestock and manure	
Presence of Livestock	Identify presence or absence of livestock	Determine whether or not waste materials are produced and managed on-site	Categorical	N/A	YES or NO	Annual	Farmer	Presence of livestock will require additional descriptions of type and stocking rate	Assume NO unless type and stocking rate are complete, then YES
Livestock Type(s)	Identify type of livestock on farm	Distinguish further between types of waste on farm	Text (dropdown list)	N/A	Up to 5 fields available to enter text (e.g. dairy cattle, sheep, etc.)	Annual	Farmer	Fields should be complete if livestock response is YES	Empty fields are expected if livestock response is NO

5.2.3.2 ENTITY RELATIONSHIP DIAGRAM

An entity relationship diagram is a database map that identifies individual tables of data inputs and describes the relationships between them. Through this schematic, any single data entry point can be traced to any other related data point. For example, an input from a field assessment has its own date and value but is also connected to the type of assessment and what ‘plot’ it is recorded from, which is designated by the specific crop, any experimental treatments applied and the location of the plot within a specific field on a specific farm in a region. This single data entry relates to every other table of input types in the database and the entity relationship diagram shows these relationships. Relational database management, including applications of entity relationship diagrams, is utilised and recommended by various agricultural database systems (van Evert *et al.*, 1999; Hunt *et al.*, 2001; White *et al.*, 2013). Prior to the creation of the MySQL database, the diagram was created by hand to plan how data entries were interconnected and reviewed with IT specialists. The final entity relationship diagram (Figure 5.2.1) was created in MySQL along with the database.

5.2.3.3 MYSQL DATABASE

MySQL is a relational database management system, using Structured Query Language (SQL) within a multiuser server to provide fast, authorised access to data (Welling and Thomson, 2009). Using the data dictionary and the hand-drawn entity relationship diagram, individual tables were created in the MySQL database using phpMyAdmin (an open source administration tool for MySQL). Within a table, each data input type is a column and was designated an ID, a name, input type (e.g. TEXT, VARCHAR, DECIMAL) and input length. Relationships were created between tables by denoting IDs as the primary key and using this key as a reference from one table to another. After populating the tables and setting the relationships between them, the final entity relationship diagram (Figure 5.2.1) was checked with IT specialists prior to building the web interface.

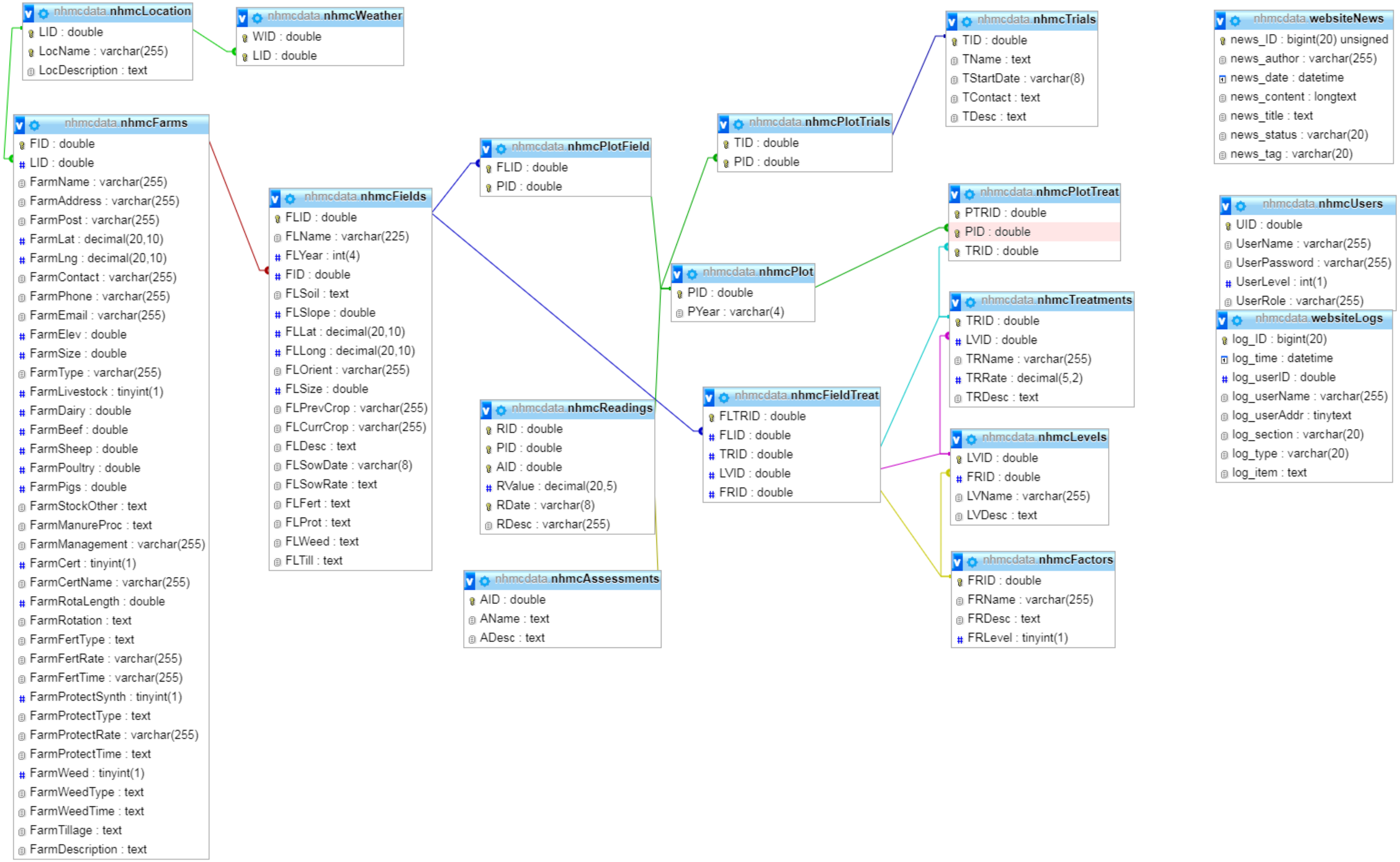

Figure 5.2.1. The MySQL Entity Relationship Diagram for the Farmer Participatory trial online database system.

5.2.3.4 WEB DATABASE

The final database required a web interface that would allow participant farmers and researchers to view and input data in an accessible format. A website hosted by Newcastle University was set-up and gradually built based on the data dictionary and required functionality of the database, using Hypertext Markup Language (HTML), JavaScript and PHP (PHP: Hypertext Preprocessor). The metadata entry pages (including historical farm management, experimental factors and assessment types) were created using HTML with Cascading Style Sheets (CSS) and JavaScript programming language. The webpages were then linked to the MySQL database using PHP scripting language to execute commands relating to the database.

The MySQL database identifies users with different levels of website access written into the PHP script on the site to allow for security and data protection. Website ‘administrators’ have full access to the database, ‘managers’ can upload, edit and view all data but cannot manipulate the website or database functionality, ‘participants’ can upload, edit and view farm and experimental field background data but cannot access assessment data, while an outside visitor to the site can only view published updates and trial results approved by the site administrators.

5.2.4 USING THE DATABASE

The final web-database was completed in early 2018, after harvest of the first year and sowing of the second and final year of the FPT. Unique ‘participant’ level usernames and passwords were circulated to all participants with instructions for accessing the site and inputting farm and field background data. ‘Manager’ level usernames and passwords were also distributed to European project partners in Estonia and the Czech Republic to use in their farmer participatory trials.

UK farmer participants were emailed and called to provide historical farm management and experimental field management information using the website. Individuals who did not use the website provided information to researchers over the phone or by email. All assessment data over the two-year trial was collected outside of the database platform due to the system not being available in the first year and troubleshooting occurring in the second year.

5.3 DISCUSSION

5.3.1 FARMER PARTICIPATION

The on-farm spelt and rye trials were participatory in that farmers grew experimental varieties on their own farms, but the planning and design of the trials placed an emphasis on the researcher as the primary experimental manager. While farmer participatory research includes a range of models for researcher-farmer relationships, there were benefits and drawbacks to a researcher-driven approach.

5.3.1.1 ENCOURAGING PARTICIPATION

One of the primary draws for farmers to join participatory research is the mitigation of risk associated with innovation. Researcher involvement reduces uncertainty for farmers, through the provision of specialised knowledge (Ashby, 1986; Ashby, 1987). On-farm strip-plots are often used by breeding companies to evaluate cultivars (Yan *et al.*, 2002; Llewellyn, 2007; ADAS, 2018), and are valuable to growers as an opportunity to try a new variety/product and find response areas within a commercial field (Hicks *et al.*, 1997). This certainly encouraged participation in the spelt and rye trials as all seed was supplied by the project, harvest was completed by the research team and participants received financial compensation to cover costs of sowing and maintaining the fields. The trials were also relatively small, taking up a maximum of 800 m^2, which meant farmers were not risking a full commercial field to participate, but were large enough for effective cultivar evaluation (Rzewnicki *et al.*, 1988; Yan *et al.*, 2002).

The on-farm trials also encouraged farmer involvement by limiting experimental factors; farmers were asked to manage the trials as they typically would any cereal crop, with researcher consultation available upon request. Only one experimental input (biogas digestate) was applied to accessible sites and this was arranged and funded by the research team to limit disruption to the farmer. Participatory trials benefit from allowing farmers to make autonomous decisions about management (Ashby, 1987) and utilising farmers' experimentation capacity (Hoffmann *et al.*, 2007). Generally, farmers prefer experimental designs that are easy to plan and implement while providing data that is transparent, easy to interpret and suitable for informing farm management decisions (Griffin *et al.*, 2008; Lawes and Bramley, 2012). Not requiring farmers to use alternative methods or input types increased their likelihood of participation and allowed them to experience how different crop varieties react within their own agronomic systems.

5.3.1.2 **BARRIERS TO PARTICIPATION**

Although the experimental design of the FPT aimed to simplify participation for farmers, the main barrier to farmer involvement in the research was that farmer participation was not included throughout the design of the project. Stakeholders and project partners in the over-arching EU HealthyMinorCereals project included farm-business owners who were consulted in the research project proposal, but individual farmers who grew spelt and rye for the trials were not involved until the recruitment process. Since the introduction of the 'farmer first' approach of the late 1980s (Chambers *et al.*, 1989), participatory research is deemed most successful in terms of recruitment and outcomes when farmers are involved at all stages, from defining research questions to formalising informal experimentation (Ashby, 1986; Ashby, 1987; Farrington and Martin, 1988; Watkins, 1990; van de Fliert and Braun, 2002; Hoffmann *et al.*, 2007; Hellin *et al.*, 2008; Neef and Neubert, 2011; Lawes and Bramley, 2012). Including farmers earlier in the process to include their input in trial-design would have encouraged collaboration and likely improved recruitment. The nature and scope of the spelt and rye trials did not facilitate this type of farmer-researcher relationship, but future FPT research utilising the online database system would benefit from earlier farmer inclusion.

The level of farmer involvement in trial design is difficult to resolve in research-driven FPT, as there is a divergence between participant and researcher objectives. As noted, farmers value straightforward and simple evaluative processes to assist with decision-making, while researchers aim to implement multi-factor experimental designs for high-impact research outcomes (Lawes and Bramley, 2012). More recent examples of FPT centering farmers as innovators also take advantage of the improved on-farm data collection technologies of precision agriculture to provide robust agronomic data that satisfy researcher requirements (MacMillan and Benton, 2014; Sylvester-Bradley *et al.*, 2017; ADAS, 2018). While precision agriculture technology was not included in the scope of the FPT, there is potential for this to be applied in the future, along with the online database. New machinery and software are increasingly available to monitor and record agronomic practices and outcomes, which provides opportunities for automated data-collection. The spelt and rye trial database was not designed with on-farm data-recording capabilities in mind, which could have simplified participant involvement. All farmers maintain their own agronomic records and at least one participant used the crop management software Gatekeeper (Farmplan). This data recording system could have served as a template for the trial database or been directly connected to the database for data transfer. Unfortunately, not every grower uses the same record-keeping systems and designing and implementing additional data-transfer technology to be compatible with each individual farm was beyond the scope of the project. Using new advances in farm-monitoring systems as data sources encourages farmers to collaborate with research platforms through tools that are already implemented on-farm and can contribute additional experimental inputs for research analysis.

5.3.2 ONLINE DATABASE

Throughout planning of the FPT, its development included an online database to facilitate data collection and monitoring. While the database and website were created for initial use by the spelt and rye trial, the intention was for the system to have the flexibility for use in other farmer participatory projects in the future.

5.3.2.1 BENEFITS OF ONLINE DATA COLLECTION

Increasingly, the Internet is used as a tool for data management and collection. Online data collection reduces response times, lowers costs, allows for flexibility and control over formatting and takes advantage of continual advances in technology (e.g. smartphone app-based platforms) (Granello and Wheaton, 2004). The goal in creating the online database was to provide time-saving flexibility for farmers; by using the website, participants uploaded data in their own time and did not need to respond to questions over phone or by mail. This functionality also served the broader European project, allowing for web access to partners in multiple countries and the flexibility to use the site to best suit their needs.

As in other business sectors, farmers are increasingly using online tools, with major growth in computer and internet-use by farmers over the past decade. Warren (2004) noted that in 2001, 60% of UK farm businesses had access to a computer and of those only 26% used the Internet for business purposes, showing a major lag in internet-use behind UK Small-to-Medium-Enterprises (SMEs) overall. More recently, Department for Environment, Food & Rural Affairs (DEFRA) surveys show that 90% of UK farm businesses had access to a computer in 2012 and of these, 87% used the Internet for submitting forms/online banking, 46% used the Internet to purchase/sell farm material, 26% used the Internet to communicate with other farms and 12% used the Internet to improve farm performance (DEFRA, 2013). Additionally, this same survey noted that 29% of farmers had a smartphone in 2012, with 89% of these using it for the farm business and a more recent study of farmers in the UK and France found that 89% of respondents owned a smartphone, of which 84% used it for farm management (Dehnen-Schmutz *et al.*, 2016). Farmer internet-use has clearly grown as technology continues to become more and more widespread in everyday communication and decision-making. Providing a web-based platform for data collection takes advantage of the increasing role of the Internet in agricultural businesses.

5.3.2.2 LIMITATIONS TO DATABASE USE

Although farmer internet and computer use has increased steadily, the coverage and speed of rural telecommunications and rate of computer/internet literacy remain barriers to farmer use of web-based technologies (Warren, 2002; Warren, 2004). The DEFRA survey found that the top five factors to encourage more computer use for farm business were: faster broadband (50%), more time (44%), improved computer skills (43%), more confidence in computer security (38%) and better quality of connection (37%) (DEFRA, 2013). The extent and quality of broadband speed in the UK falls outside of the purview of the spelt and rye project, however the expectation of regular and confident computer and internet-usage by participants likely contributed to low database-use from participant farmers. Some farmers were very responsive to email communication while others were best contacted by phone. The online nature of the database entry forms were not the preferred method of providing research data for some participants and they required more time and direct interaction with researchers to submit information.

Lower response rates are not uncommon in online data collection; web-based surveying methods have higher initial response rates but lower overall response rates than traditional paper surveys (Ladner *et al.,* 2002). Multiple reminders can offset this effect (Granello and Wheaton, 2004), which was employed in encouraging participant use of the database, however late website availability was a major limitation to participant database-use. The full website was not available to participants until after the first year of data was already collected and the second year trial had been sown. Farmers did not view the online database as an integral part of the research project because it was not available from the beginning of the trial. Online data collection is more successful if systems are trialled in pilot studies and have troubleshooting opportunities outside of final data collection (Granello and Wheaton, 2004). Although the web-platform was live before the completion of the trial, this left no opportunity for a trial period and did not emphasise to participants that using the website was an essential component of data collection. Those individuals with limited computer and/or internet experience would also likely benefit from instructive tutorials on the database system prior to data entry, which is recommended in the future.

5.3.2.3 USING THE DATABASE

Modern agro-ecological databases models help facilitate the collection and management of data from multisite experiments (van Evert *et al.*, 1999) and are used to store and share information between farmers, plant breeders and researchers (Fox *et al.*, 1997; Haley *et al.*, 1999; Hunt *et al.*, 2001). The database created for the spelt and rye trials was used to facilitate the FPT and has the potential to be used as a dissemination and knowledge-sharing platform in the future.

Although the online database was not available throughout the FPT, the platform was useful in data collection, particularly for historical farm and field management information. In the UK, all participants except one used the online database to enter farm background data and experimental field management information (Table 5.3.1 & Table 5.3.2). Some data input types (location and map coordinates) were entered by the researcher prior to farmer database access, but otherwise most data entries were completed by farmer participants. The scale of the FPT does not include enough participants to statistically evaluate database-use figures. Based on follow-up communication to obtain missing data, some items (e.g. farm elevation, field slope) were not immediately at hand when farmers accessed the database and others required additional clarification (e.g. crop rotation) (Table 5.3.2). For field data, most particpants included any experimental management data, with the exception of farm fertility, which was left blank by many organic growers because no inputs were included and ultimately confirmed by the researcher (Table 5.3.2). The participants who used the platform provided necessary metadata by accessing the site and entering the data successfully, demonstrating the database's functionality.

Table 5.3.1. The number of particpants, organic and conventional farmers and participant database users across all three partner countries in the Farmer Participatory trial over the two trial years.

	United Kingdom^{+}	Estonia	Czech Republic
Total Participants	9	8	8
Organic Farms	*5*	*4*	*4*
Conventional Farms	*4*	*4*	*4*
Participants Using Database	8	0	0

$^{+}$The different number of total participants and organic farms in the UK compared to other countries reflects the change in participants between trial years.

Additionally, the data entry pages on the site served as a template 'survey', which was used in follow-up phone calls to participant farmers and was the basis for data collection by European project partners. Due to the delayed web-platform availability, no farmer participants outside of the UK uploaded any data onto the database site (Table 5.3.1), but researchers in Estonia used the format of the data entry pages to collect historical farm and field data from participants over the phone, in person and by email (Table B.2. & Table B.3., Appendix B). While the site is intended for direct use by farmers, it also facilitated data collection by providing data entry templates for researchers working in multiple sites, indicating that the online database created for the FPT is a functional tool for agricultural research.

Table 5.3.2. Number of database entries completed by farmers or researchers for different farm background and experimental field management data input types in the UK Farmer-Participatory Trial. Farm background data applied to a total of 9 farms while field management data applied to a total of 14 sites over the 2016-2017 and 2017-2018 trial years.

Farm Background Data			**Field Management Data**		
Input Type	**Researcher**	**Farmer**	**Input Type**	**Researcher**	**Farmer**
Location	9	0	Soil	1	13
Coordinates	9	0	Slope	9	5
Elevation	6	3	Orientation	2	12
Size	5	4	Size	7	7
Type	1	8	Cropping	1	13
Management	1	8	Farm Fertility	7	7
Certification	1	8	Crop Protection+	1	5
Livestock	1	8	Weeding	1	13
Waste Process	2	7	Tillage	1	13
Crop Rotation	6	3			
Fertility	2	7			
Pesticide	2	7			
Weeding	1	8			
Tillage	2	7			

+Only conventionally managed sites were required to include crop protection inputs, which was a total of 6 sites

Beyond compiling data for this research project, the database can serve as a platform to link stakeholders together, through dissemination, data sharing and future on-farm trials. The website has a news items functionality that was used to provide simple project updates throughout the project and is capable of presenting research summaries at the conclusion of the project.

5.3.2.4 FUTURE DATABASE APPLICATIONS

The growth of web-based platforms for use in agriculture are also beneficial for decision-making and research due to convenience (Bostick *et al.*, 2004) and there is great potential for online systems to facilitate knowledge exchange in agriculture, especially by improving information accessibility (Bruce, 2016). The online database created for the FPT is intended for use beyond the spelt and rye trials. Farmer and researcher use of the database through the on-farm trials demonstrates the web platform's functionality and utility as a data collection tool and its continued use will improve its ability to assist decision-making and knowledge exchange.

5.4 CONCLUSIONS

The creation and use of an online database for the Farmer Participatory spelt and rye trials demonstrates the practicality of a web-based data collection platform and the potential for further on-farm participatory trials with greater farmer input.

The FPT serves as an example of researcher-led participatory research, which was effective in assessing experimental varieties and inputs across multiple sites through web-based data collection. Recruitment through dissemination events and direct contact with farmers established a small network of participants who were able to access and use the online database to enter historical field and farm management information. The database website also served as a template for European partners to collect background data from farmers within their own trials, demonstrating potential for knowledge exchange on the web platform.

The use of the web database demonstrates the potential for future participatory trials using the platform, with the knowledge that encouraging farmer input earlier in the experimental design process and providing website availability earlier in the trial period will improve participant recruitment and database-use. The FPT served as a preliminary example of the collaborative research that is possible through online database-facilitated participatory trials.

CHAPTER 6. FARMER PARTICIPATORY TRIALS

Evaluating the yield and quality of spelt and rye in Farmer Participatory trials

6.1 INTRODUCTION

The spelt and rye field trials at Nafferton farm evaluated both old and new genotypes with alternative fertilisers in controlled experimental conditions, providing insight into successful varieties and fertility regimes. The results of small-plot, single-site experiments do not always reflect how crops and inputs will react on a commercial scale, therefore the trial continued through a Farmer Participatory trial to consider the viability of the spelt and rye varieties across multiple sites and management systems in the North East UK.

Farmer participatory trials allow for the evaluation of experimental techniques under realistic farm conditions, providing insight to farmers and researchers about how research-tested methods will perform under conditions where they were intended to be employed (Lockeretz, 1987; Rzewnicki *et al.*, 1988). Participatory trials seek to extend the scope of research across sites and transfer technology, as farmers are encouraged to utilise the practices under evaluation (Witcombe, 1999).

Spelt and rye are both considered well-suited for low-input and organic farming systems. Rye is valued for high winter hardiness, tolerance of poor climatic conditions and poor soil fertility and low susceptibility to leaf disease (Bushuk, 2001; Schlegel, 2014), while spelt responds well to low-input fertility and is able to grow in harsh/varied climatic conditions (Bonafaccia *et al.*, 2000). Growing spelt and rye on different farms (both organic and conventional) with different farming practices provides an opportunity to consider how genotypes respond to different agronomic systems and determine the viability of low-input techniques on a larger scale.

This chapter evaluates the yield and quality performance of European spelt and rye varieties grown on different organic and conventional farms in the Northeast of England.

6.2 MATERIALS AND METHODS

6.2.1 EXPERIMENTAL DESIGN

The effects of management, fertiliser type and variety choice on crop yield and quality were assessed in spelt and rye in a two-year Farmer Participatory trial. Crop health assessments, including disease severity and SPAD readings, were carried out throughout the growing season in both years. Grain yield and yield components were determined at harvest, including total biomass, combine yield, thousand grain weight and harvest index. Harvested grain was further analysed for grain quality parameters, including Hagberg Falling Number, specific weight and protein content.

6.2.1.1 SITE DESCRIPTIONS

The on-farm trials were located at twelve different sites in northeast England (Figure 6.2.1), and carried out over two consecutive growing seasons (2016-17 and 2017-18 respectively, referred to throughout as 2017 and 2018). Historical farm background data from each farm can be found in Appendix C (Table C.1. & Table C.2.). Background data from each site, including location coordinates, soil type, field size and cropping are in Table C.3. (Appendix C). Soil samples were collected at 30cm depths from all sites over 6-7 February 2017 and 2 February 2018 and analysed for pH, P, K and Mg (Table 3.2.1).

6.2.1.2 EXPERIMENTAL LAYOUT

Each on-farm trial was sown in 100m x drill width (3m or 4m depending on individual farms) non-replicated strip plots by variety in an individual field selected by each participatory farmer. Participants received seed for each variety and drilled the strip plots individually, following instructions provided by the research team. All sites in both years were sown in the same variety order (Figure 6.2.2 & Figure 6.2.3), while two sites requested sowing the spelt and rye in consecutive blocks in 2018 (Figure 6.2.4 & Figure 6.2.5) and one site misinterpreted instructions and sowed individual spelt and rye varieties side-by-side in 2018 (Figure 6.2.6). A single experimental fertiliser input (biogas digestate) was applied to four sites in 2017 and three sites in 2018 based on location and availability. In these fields, biogas digestate was applied to one-half of each variety strip, such that 50m x drill width of each variety was fertilised with biogas digestate while the other 50m x drill width was fertilised with typical inputs used by the host farm (Figure 6.2.7). Trial sites without digestate were fertilised based on standard farm management practices.

Figure 6.2.1. Map locations of the twelve spelt and rye Farmer Partcipatory trial sites (Magistrali, 2019). Orange markers indicate sites only in 2017; blue markers indicate sites only in 2018; green markers indicate sites used in both trial years. Additional map locations based around the northern-most sites (Figure C.1), sites near Nafferton (Figure C.2) and Gibside (Figure C.3) are in Appendix C.

Table 6.2.1 Soil pH and phosphorus, potassium and magnesium index at each Farmer Participatory trial site in 2017 and 2018.

Year	Site	Soil pH	P Index	P mg/l	K Index	K mg/l	Mg Index	Mg mg/l
2017	Gibside	6.6	1	10.8	1	114	4	177
	Gilchesters 1	6.3	1	11.4	2-	145	3	149
	Moorhouse	7.2	0	7.8	0	44	3	111
	Newlands	6.2	1	11.6	1	65	3	131
	Quarry	6.7	0	9.4	1	100	3	130
	Spindlestone	7.6	2	18.4	1	89	3	118
	Wheldon	6.3	1	11.6	1	81	3	168
2018	Applebys Whin	7.0	0	6.2	1	69	4	178
	Gilchesters 2	6.5	1	11.2	3	289	4	242
	Moorhouse	7.2	0	7.8	1	64	3	134
	Pawson	6.8	2	15.6	1	82	3	165
	Three-Cornered	6.3	1	12.2	2-	153	3	109
	Tughall	5.9	0	6.2	0	48	3	105
	Wheldon	6.4	1	10.4	1	76	3	142

Ten samples randomly collected throughout the trial area were collected and bulked at 30cm-depths on 6-7 February 2017 and 2 February 2018. Samples were analysed by NRM Laboratories (Bracknell, Berkshire).

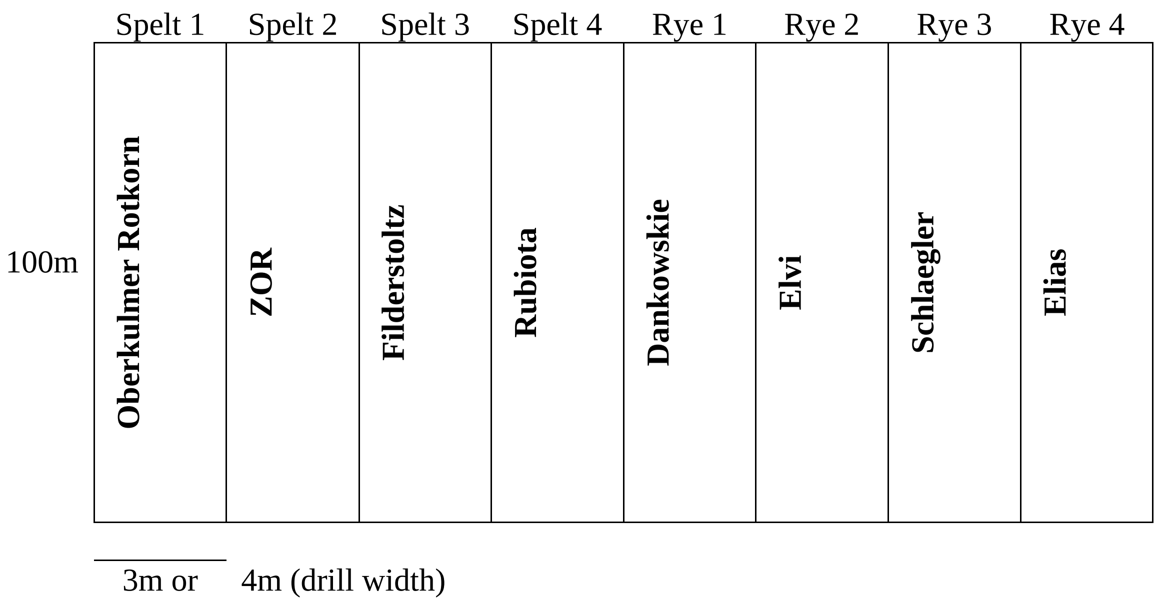

Figure 6.2.2. Field trial design for the Farmer Participatory spelt and rye trials. The layout was provided to each farmer to describe how experimental varieties should be sown at each site.

Figure 6.2.3. The Farmer Participatory trial based on the layout depicted in Figure 6.2.2. Spelt is in the foreground while rye is in the background.

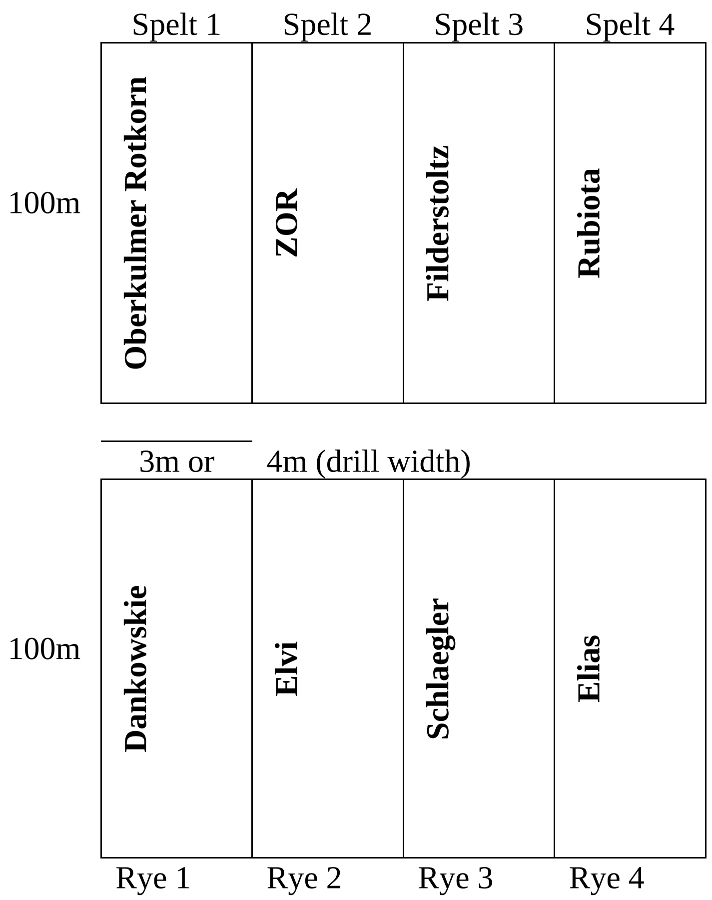

Figure 6.2.4. Alternative field trial design for the Farmer Participatory spelt and rye trials. The layout was provided to farmers who requested sowing spelt and rye in consecutive blocks to describe how experimental varieties should be sown at each site.

Figure 6.2.5. The Farmer Participatory trial based on the layout depicted in Figure 6.2.4. Spelt is in the foreground while unestablished rye is in the background.

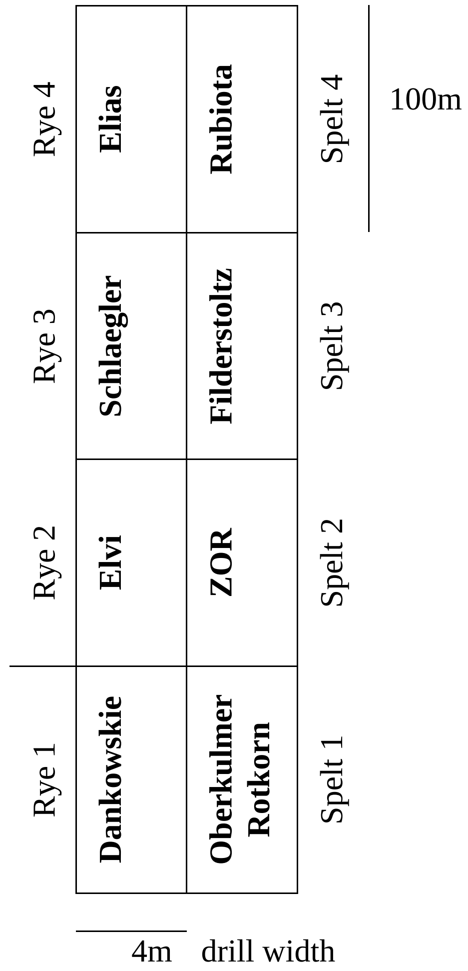

Figure 6.2.6. Alternative field trial design for the Farmer Participatory spelt and rye trials used by one participant in 2018 trial (based on misinterpretation of original field trial design).

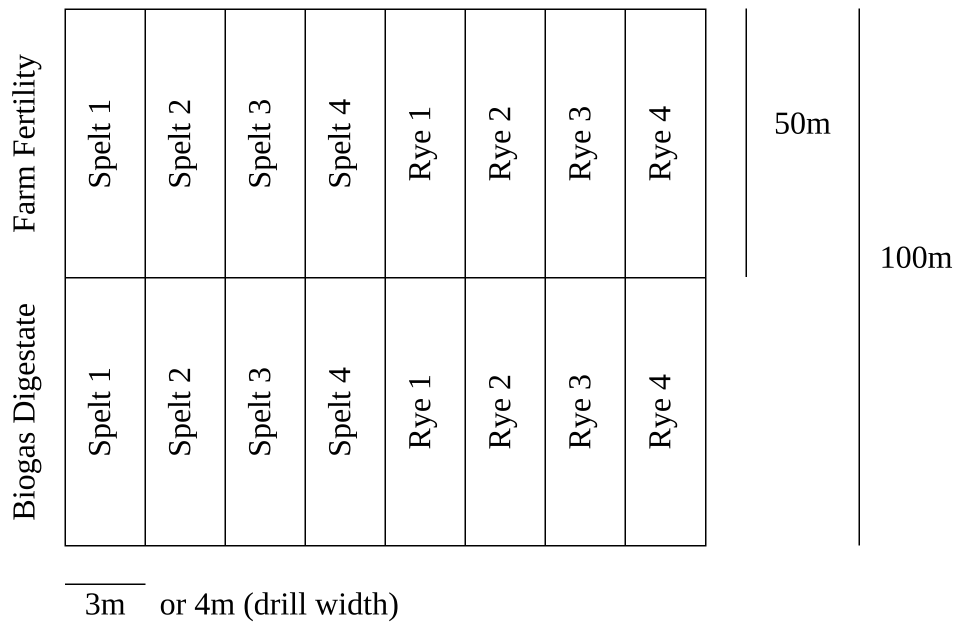

Figure 6.2.7. Field trial design for the Farmer Participatory spelt and rye trials including experimental fertiliser inputs.

6.2.1.3 AGRONOMIC MANAGEMENT

The FPT trials included the same four spelt and rye varieties included in the field trials described in Chapters 3 and 4. The spelt varieties included: Oberkulmer Rotkorn (Ob Rot), Zuercher Oberlaender Rotkorn (ZOR), Rubiota (Rub) and Filderstolz (Fild); the rye varieties included: Elvi, Elias, Dankowskie Amber (Dank) and Schlaegler (Sch). Seed was provided by EU partners in the HealthyMinorCereals project and sown at uniform rates across all sites for the 2017 trial (Table 6.2.2). The remainder of this seed was used for the 2018 trial, as well as additional seed from HMC partners and seed from a single farm's harvest from the 2017 on-farm trial (Table 6.2.3). Participants sowed varieties on dates that were most convenient for them after receiving the seed (Table 6.2.4).

Biogas digestate was the only experimental input included in the FPT and was supplied by DJ & SJ Enderby Recycling (Hexham, Northumberland). Digestate was applied at a rate of 100kg N/ha based on total N in the BD in each year (Table 3.2.5). Digestate was applied to four sites in 2017 and three sites in 2018 (Table 6.2.4), based on field accessibility and organic certification permissions. All other fertiliser inputs were based on each site's typical management practices (Table C.4., Appendix C) and any crop protection methods were applied by farmers based on typical practices (Table C.5., Appendix C).

Table 6.2.2. Seed rates in kg/ha for spelt and rye varieties sown in the 2017 Farmer Participatory trials.

Spelt	
Oberkulmer Rotkorn	290
ZOR	290
Rubiota	290
Filderstolz	290
Rye	
Dankowskie Amber	114
Elvi	87
Schlaegler	97
Elias	133

All spelt varieties were drilled at 250 hulled seeds/m^2 and all rye varieties at 350 seeds/m^2.

Table 6.2.3. Seed rates and source by variety for spelt and rye grown in the Farmer Participatoyr trial in 2018.

Site	Variety	Source	Rate (kg/ha)	Site	Variety	Source	Rate (kg/ha)
Applebys	Ob Rot	FPT17	204	Three-	Ob Rot	HMC16	290
Whin	ZOR	HMC16	290	Cornered	ZOR	HMC16	290
	Fild	FPT17	134		Fild	HMC16	290
	Rub	FPT17	209		Rub	FPT17	209
	Dank	FPT17	87		Dank	HMC16	114
	Elvi	HMC17	123		Elvi	HMC17	123
	Sch	HMC17	102		Sch	HMC17	102
	Elias	HMC16	133		Elias	FPT17	96
Gilchesters 2	Ob Rot	FPT17	204	Tughall	Ob Rot	HMC16	290
	ZOR	FPT17	459		ZOR	HMC16	290
	Fild	FPT17	134		Fild	HMC16	290
	Rub	FPT17	209		Rub	FPT17	209
	Dank	FPT17	87		Dank	FPT17	87
	Elvi	FPT17	89		Elvi	HMC17	123
	Sch	FPT17	87		Sch	HMC17	102
	Elias	FPT17	96		Elias	FPT17	96
Moorhouse	Ob Rot	HMC16	290	Wheldon	Ob Rot	HMC16	290
	ZOR	HMC16	290		ZOR	HMC16	290
	Fild	HMC16	290		Fild	HMC16	290
	Rub	HMC16	290		Rub	HMC16	290
	Dank	HMC16	114		Dank	HMC16	114
	Elvi	HMC16	87		Elvi	HMC16	87
	Sch	HMC16	97		Sch	HMC16	97
	Elias	HMC16	133		Elias	HMC16	133
Pawson	Ob Rot	HMC16	290				
	ZOR	HMC16	290				
	Fild	HMC16	290				
	Rub	HMC16	290				
	Dank	HMC16	114				
	Elvi	HMC16	87				
	Sch	HMC16	97				
	Elias	HMC16	133				

All spelt varieties were drilled at 250 hulled seeds/m^2 and all rye varieties at 350 seeds/m^2.
FPT17—Seed sourced from harvest at a single farm in the 2017 Farmer Participatory trial.
HMC16—Seed sourced from HealthyMinorCereals project partners in 2016.
HMC17—Seed sourced from HealthyMinorCereals project partners in 2017.

Table 6.2.4. Sowing, biogas digestate applications and harvest dates for spelt and rye grown in Farmer Participatory trials in 2017 and 2018.

Site	Sowing Date	BD Spread Date	Biomass Harvest Date	Combine Harvest Date	Combine Type
			2017		
Gibside	27 Oct 2016	16 May 2017	25 Aug 2017	4 Sept 2017	Claas 25
Gilchesters 1	4 Nov 2016	16 May 2017	29 Aug 2017	27 Sept 2017	JD 2264
Moorhouse	4 Nov 2016	15 May 2017	24 Aug 2017	20 Sept 2017	Claas 38t
Newlands	28 Oct 2016	Not Applied	25 Aug 2017	6 Sept 2017	Claas 25
Quarry					
Spelt	29 Oct 2016	15 May 2017	24 Aug 2017	30 Aug 2017	Claas 38
Rye				20 Sept 2017	
Spindlestone	28 Oct 2016	Not Applied	25 Aug 2017	27 Oct 2017	Massey 525
Wheldon	19 Oct 2016	Not Applied	23 Aug 2017	30 Aug 2017	Claas 38
			2018		
Applebys Whin	1 Nov 2017	Not Applied	15 Aug 2018	30 Aug 2018	Claas 25
Gilchesters 2	17 Oct 2017	08 May 2018	14 Aug 2018	12 Sept 2018	Claas 38
Moorhouse	3 Oct 2017	08 May 2018	16 Aug 2018	6 Sept 2018	Claas 25
Pawson					
Spelt	27 Sept 2017	08 May 2018	14 Aug 2018	28 Aug 2018	Claas 38
Rye			16 Aug 2018	31 Aug 2018	
Three-Cornered	30 Oct 2017	Not Applied	15 Aug 2018	29 Aug 2018	Claas 25
Tughall	26 Oct 2017	Not Applied	15 Aug 2018	30 Aug 2018	Claas 25
Wheldon	27 Sept 2017	Not Applied	13 Aug 2018	28 Aug 2018	Claas 38

Combine types: Claas 25—Claas Compact 25 plot combine; Claas 38—Claas Dominator 38 plot combine; JD 2264—John Deere 2264 Hillmaster; Massey 525—Massey Ferguson 525
NB: All spelt and rye varieties were harvested on the same date unless otherwise specified for each crop (e.g. Quarry 2017 and Pawson 2018).

Table 6.2.5. Nutrient content of biogas digestate used in the Farmer Participatory trial in 2017 and 2018.

	2017	**2018**
Total N (% dry matter)	4.48	5.80
Total P (mg/kg)	668	949
Total K (mg/kg)	5071	4885
Total Mg (mg/kg)	349	511

Digestate samples were analysed by NRM Laboratories (Bracknell, Berkshire).

6.2.2 EXPERIMENTAL ASSESSMENTS

6.2.2.1 GROWING SEASON ASSESSMENTS

A single plant count took place in January of both trial years. Throughout the growing period, spelt and rye leaves were monitored for the key foliar disease powdery mildew (*Blumeria graminis*) and leaf blotch (*Septoria tritici* and *Septoria secalis*), as well as yellow stripe rust in spelt (*Puccinia striiformis*) and brow leaf rust (*Puccinia recondite*) in rye. Beginning at GS37 in spelt and GS47 in rye, disease assessments occurred every two weeks through to maturity.

Each FPT site was sampled following the same process (Figure 6.2.8), moving across the width of each variety and pausing to assess the top four leaves of five randomly selected plants for presence and severity of disease and then sampling another five plants further along the strip. Following this pattern, a total of ten plants were sampled for each variety/fertiliser type combination. At GS82/83, crops were assessed for fusarium head blight (*F. graminearum*), ergot (*Claviceps purpurea*) and *P. striiformis* in the ear by selecting ten tillers for each variety/fertiliser type and examining ears for disease presence and severity. Leaves and ears were scored in the same manner, given a rating of 0 (no disease present), 1%, 5%, 10%, 25%, 50%, 75% or senesced. Scores from each sample were averaged to provide measurement for each plot, which was used with assessment date to collate an Area Under the Disease Progress Curve (AUDPC) (Jeger, 2004).

Indirect leaf chlorophyll concentration measurements were taken with a SPAD hand-held chlorophyll meter (SPAD 502 Plus). Following the same assessment pattern used for disease severity (Figure 6.2.8), SPAD readings were taken on the flag leaf of ten plants for each variety/fertiliser type combination. Chlorophyll readings were recorded at the same time as disease assessments, with five readings taken throughout the growing season.

Plant height measurements were taken at anthesis (GS68) and during biomass harvest by selecting six plants within each variety/fertiliser type combination and measuring from ground level to the top of the ear. The six heights from each sample were averaged to provide a plant height measurement.

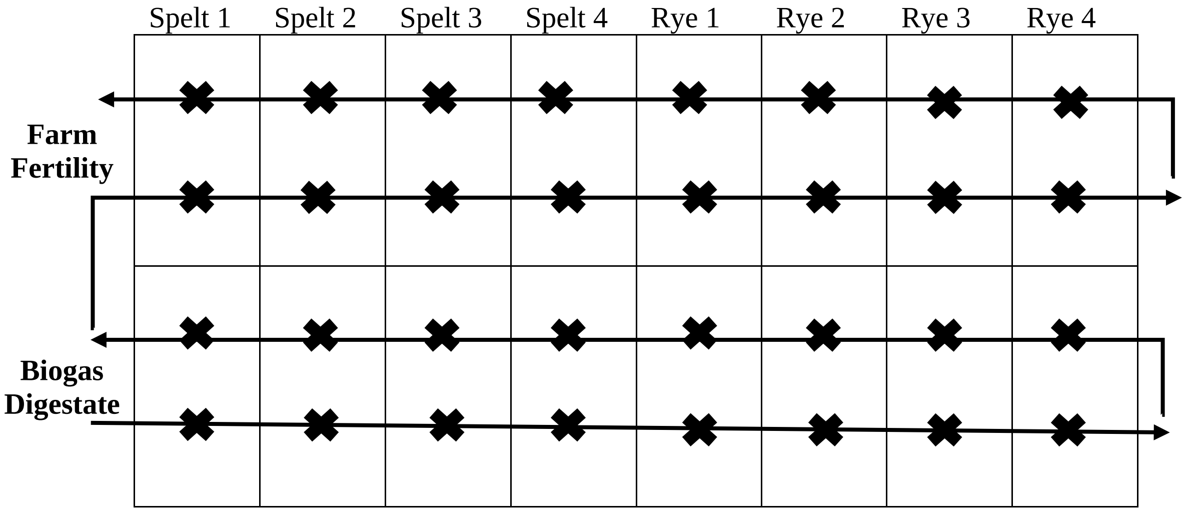

Figure 6.2.8. The Farmer Participatory trial sampling pattern used at each on-farm trial site. The ✖ identifies a sampling location within a variety strip. This figure represents the pattern for sites with biogas digestate fertiliser inputs. Sites without digestate applications were sampled in a similar manner but only as one full variety strip rather than in separate fertility sections.

6.2.2.2 GRAIN YIELD ASSESSMENTS

Prior to harvest, biomass samples were removed from each strip plot to assess total biomass, harvest index, moisture content and additional yield components. Plants from 4 x $0.25m^2$ quadrats were counted and removed from each strip plot following the FPT sampling pattern (Figure 6.2.8). In fields with biogas digestate, an additional $0.25m^2$ quadrat was sampled on each half of the strip plot for a total of 3 x 0.25 m^2 quadrats for each variety/fertiliser type combination. In 2017, biomass samples were collected from 24-29 August; in 2018, samples were collected from 13-16 August (Table 6.2.4). Crops were harvested with a plot combine (Claas Dominator 38 or Claas Compact 25; Class UK Ltd, Bury St Edmunds UK), except when the plot combine was unavailable at two sites in 2017, in which case variety strips were harvested with alternative combines (Table 6.2.4), which were emptied and weighed after each strip. A sample of grain (3-5 kg) was taken and used for grain quality assessments. Lodging severity was also recorded at harvest, based on a scale from 0-9, with 0 reflecting no lodging and 9 indicating that plants lay completely flat. In 2017, harvest occurred at the end of August and into mid-late September (and late October at one site) after one of the plot combines broke; in 2018 crops were harvested 28 August-12 September (Table 6.2.4). Harvest index was calculated as the ratio between grain yield and total crop biomass.

6.2.2.3 YIELD COMPONENT ASSESSMENTS

Biomass harvest samples were individually processed for each variety/fertiliser type combination as described in Chapter 3.

Rye combined grain and biomass ear samples were dried, cleaned and threshed at Nafferton farm using a seed cleaner and thresher. Spelt is combined with a hull and was dried at Nafferton farm then de-hulled and cleaned using a small de-huller at Gilchesters Organics (Stamfordham, Northumberland).

Yield component assessments were completed following the methods described in Chapter 3

6.2.2.4 GRAIN MILLING QUALITY ASSESSMENTS

Sub samples of 500 grams from each sample were taken to Coastal Grains Ltd (Belford, Northumberland) to measure Hagberg Falling Number, specific weight and protein content as described in Chapter 3.

6.2.3 STATISTICAL ANALYSIS

Due to poor establishment/slug damage in the rye at multiple sites in both trial years, the rye dataset was analysed through descriptive statistics, primarily means and standard errors. The spelt data was divided into two primary datasets for analysis:

- Dataset A: All FPT sites (n=12) and no biogas digestate fertiliser inputs;
- Dataset B: All FPT sites except Spindlestone (n=11) and no biogas digestate fertiliser inputs.

Spindlestone was excluded from analysis for any data relating to harvest (grain yield, harvest index, yield components) or grain quality due to an exceptionally late harvest date (27 October), which compromised harvest yields and grain quality. An additional secondary dataset included only FPT sites that applied biogas digestate (n=6).

Spelt data analysis was completed using the Linear and Nonlinear Mixed Effects Models (nlme) and Simultaneous Inference in General Parametric Models (multcomp) packages in the statistical software R (R Core Team, 2018).

ANOVAs from linear mixed-effects (lme) models from 'nlme' were used to assess the effects of fertiliser type, management and genotype on measured parameters. The first dataset, without biogas digestate, was analysed by a two-way ANOVA (management x variety); the second dataset, with biogas digestate, was analysed by a two-way ANOVA (management x fertiliser type x variety) with year designated in the random error structure of the model. In both lme models, year was included in the random error structure and means and standard errors are present in the results tables.

If significant differences (p-value <0.05) occurred between varieties and/or interactions between factors, general linear hypothesis tests (Tukey contrasts) were performed using the 'glht' function in the 'multcomp' package, with year included in the random error structure.

6.3 SPELT RESULTS

6.3.1 GRAIN HARVEST

6.3.1.1 GRAIN YIELD

Significant main effects of management were detected for spelt grain yield ($p = 0.002$); grain yield was significantly higher on conventional farms than organic farms (Table 6.3.1). On farms receiving biogas digestate, management was also highly significant ($p < 0.001$) and yield was significantly higher on conventional farms than organic farms but fertiliser type did not have a significant effect on grain yield (Table 6.3.3). Yield was higher in 2018 compared to 2017 based on both datasets (Table 6.3.1 & Table 6.3.3).

In 2017, Oberkulmer Rotkorn produced the highest yields and Rubiota the lowest; in 2018, ZOR produced the highest yields and Rubiota the lowest again (Table 6.3.2).

Spelt yield was highest at Wheldon, Moorhouse and Newlands in 2017 and at Pawson, Three-Corners and Moorhouse in 2018 (Table 6.3.4). The lowest yielding sites were Spindlestone, Quarry and Gilchesters 1 in 2017 and Applebys Whin and Gilchesters 2 in 2018 (Table 6.3.4).

6.3.1.2 PLANT HEIGHT

Significant main effects of management were detected for spelt plant height ($p = 0.047$); plants grown in organic systems were significantly taller than plants grown in conventional systems (Table 6.3.1). Highly significant main effects of variety were detected for spelt plant height ($p < 0.001$); Oberkulmer Rotkorn and Rubiota were significantly taller than Filderstolz and ZOR (Table 6.3.1). On farms receiving biogas digesate, variety was highly significant ($p < 0.001$) and Oberkulmer Rotkorn and Rubiota were significantly taller than other varieties but fertiliser type and management did not have significant effects on plant height (Table 6.3.3). Plants were taller in 2018 compared to 2017 based on both datasets (Table 6.3.1 & Table 6.3.3).

6.3.1.3 HARVEST INDEX

Harvest index did not differ significantly by management, variety or fertiliser type. HI was higher in 2018 compared to 2017 based on both datasets (Table 6.3.1 & Table 6.3.3).

6.3.1.4 LODGING SEVERITY

Significant main effects of variety ($p = 0.039$) were detected for lodging severity; lodging in Oberkulmer Rotkorn and Rubiota was significantly higher than in Filderstolz and ZOR (Table 6.3.1). On the farms receiving biogas digestate, management was highly significant for lodging severity ($p < 0.001$); lodging severity was significantly higher in spelt under conventional management compared to organic management (Table 6.3.3). Fertiliser type did not have significant effects on lodging, but lodging severity was higher in 2018 than 2017 based on both datasets (Table 6.3.1 & Table 6.3.3).

In 2017, some lodging occurred at Newlands and Wheldon but not at any other FPT site; lodging was most severe at Pawson in 2018 and was also recorded at Moorhouse, Wheldon and Tughall (Table 6.3.4).

Table 6.3.1. Main effect means, ±SE and p-values for the effects and interactions of management and variety on spelt yield, plant height, harvest index (HI) and lodging severity.

	Grain Yield (t/ha)		**Plant Height (cm)**		**HI (%)**		**Lodging Severity⁺**	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	2.13 ± 0.181	24	102.7 ± 3.19	28	26.0 ± 0.94	24	1.00 ± 0.471	28
2018	3.05 ± 0.267	28	109.6 ± 3.55	28	32.8 ± 0.99	28	2.71 ± 0.724	28
Management								
Conventional	3.15 ± 0.275	24	101.2 ± 4.25	24	29.6 ± 1.24	24	2.21 ± 0.742	24
Organic	2.18 ± 0.196	28	109.8 ± 2.64	32	29.7 ± 1.14	28	1.59 ± 0.546	32
Variety								
Fild	2.60 ± 0.420	13	94.6 ± 4.25 b	14	30.5 ± 1.45	13	0.50 ± 0.374 b	14
Ob Rot	2.72 ± 0.395	13	113.7 ± 4.27 a	14	28.3 ± 1.79	13	2.93 ± 1.102 a	14
Rub	2.49 ± 0.287	13	116.3 ± 4.47 a	14	28.2 ± 1.42	13	3.29 ± 1.071 a	14
ZOR	2.69 ± 0.339	13	99.8 ± 4.03 b	14	31.7 ± 1.91	13	0.71 ± 0.578 b	14
ANOVA *p*-values								
Main Effects								
man	**0.002**		**0.047**		NS		NS	
var	NS		**<0.001**		NS		**0.039**	
Interactions								
man:var	NS		NS		NS		NS	

⁺Lodging severity is measured on a 0-9 scale (0=upright; 9=flat).
Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVAs. Data from the site Spindlestone were excluded from the grain yield and HI analyses.

Table 6.3.2. Interaction means ±SE for the effects of trial year and variety on spelt grain yield.

	Grain Yield (t/ha)			
	Filderstolz	**Ob Rotkorn**	**Rubiota**	**ZOR**
2017	2.07 ± 0.484	2.34 ± 0.409	1.96 ± 0.205	2.15 ± 0.382
2018	3.06 ± 0.642	3.05 ± 0.649	2.94 ± 0.450	3.15 ± 0.495

Data from the site Spindlestone were excluded from the analysis. Biogas digestate treatments were not included in the analysis

Table 6.3.3. Main effect means, ±SE and p-values for the effects and interactions of management, fertiliser type and variety on spelt yield, plant height, harvest index (HI) and lodging severity.

	Grain Yield (t/ha)		**Plant Height (cm)**		**HI (%)**		**Lodging Severity**$^{+}$	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	2.01 ± 0.128	32	98.3 ± 2.55	32	26.6 ± 1.03	32	0.44 ± 0.304	32
2018	3.34 ± 0.326	24	113.8 ± 3.10	24	31.0 ± 0.62	24	4.71 ± 0.837	24
Management								
Conventional	3.06 ± 0.203	40	106.0 ± 2.94	40	28.0 ± 0.86	40	3.00 ± 0.624	40
Organic	1.37 ± 0.089	16	102.1 ± 2.41	16	29.7 ± 1.20	16	0.44 ± 0.438	16
Fertiliser Type								
Bio Digestate	2.69 ± 0.249	28	107.5 ± 2.82	28	29.1 ± 1.11	28	2.64 ± 0.728	28
Farm	2.46 ± 0.261	28	102.3 ± 3.38	28	27.9 ± 0.88	28	1.89 ± 0.651	28
Variety								
Fild	2.41 ± 0.371	14	93.6 ± 4.01 b	14	29.4 ± 1.42	14	1.00 ± 0.492	14
Ob Rot	2.59 ± 0.364	14	110.3 ± 4.28 a	14	27.5 ± 1.28	14	2.57 ± 1.128	14
Rub	2.57 ± 0.292	14	114.8 ± 4.25 a	14	27.7 ± 1.41	14	3.57 ± 1.157	14
ZOR	2.74 ± 0.429	14	100.9 ± 3.06 b	14	29.4 ± 1.61	14	1.93 ± 0.940	14
ANOVA *p*-values								
Main Effects								
man	**<0.001**		NS		NS		**<0.001**	
ft	NS		NS		NS		NS	
var	NS		**<0.001**		NS		NS	
Interactions								
man:ft	NS		NS		NS		NS	
man:var	NS		NS		NS		NS	
ft:var	NS		NS		NS		NS	
man:ft:var	NS		NS		NS		NS	

$^{+}$Lodging severity is measured on a 0-9 scale (0=upright; 9=flat).
Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

Table 6.3.4. Means ±SE for the effects of year and site on spelt grain yield and lodging severity.

Site	Grain Yield (t/ha) mean ± SE	n	Lodging Severity+ mean ± SE	n
2017				
Gibside	2.35 ± 0.217	4	0.00 ± 0.000	4
Gilchesters 1	1.21 ± 0.101	4	0.00 ± 0.000	4
Moorhouse	2.63 ± 0.379	4	0.00 ± 0.000	4
Newlands	2.59 ± 0.211	4	3.50 ± 2.021	4
Quarry	1.11 ± 0.266	4	0.00 ± 0.000	4
Spindlestone	0.42 ± 0.076	4	0.00 ± 0.000	4
Wheldon	2.89 ± 0.453	4	3.50 ± 2.021	4
2018				
Applebys Whin	0.84 ± 0.292	4	0.00 ± 0.000	4
Gilchesters 2	1.38 ± 0.125	4	0.00 ± 0.000	4
Moorhouse	4.04 ± 0.155	4	5.50 ± 2.021	4
Pawson	4.52 ± 0.452	4	7.75 ± 2.947	4
Three Corners	4.25 ± 0.115	4	0.00 ± 0.000	4
Tughall	3.41 ± 0.105	4	1.50 ± 1.500	4
Wheldon	2.91 ± 0.090	4	4.25 ± 2.462	4

+Lodging severity is measured on a 0-9 scale (0=upright; 9=flat).
Biogas digestate treatments were not included in the analysis

6.3.2 YIELD COMPONENTS

Significant main effects of management were detected for spelt ears/m^2 ($p = 0.043$) and grains/m^2 ($p = 0.036$), which were both significantly higher under conventional management than organic management (Table 6.3.5). Significant main effects of variety were detected for TGW ($p = 0.008$); Rubiota TGW was significantly lower than all other varieties (Table 6.3.5). Significant effects of fertiliser type were detected for grains/m^2 ($p = 0.049$); biogas digestate produced higher grains/m^2 than farm-based fertility (Table 6.3.6). On farms receiving biogas digestate, management was also significant for ears/m^2 ($p = 0.002$) and grains/m^2 ($p < 0.001$), while variety was significant for TGW ($p = 0.032$); both ears and grains/m^2 were higher when managed conventionalally and Rubiota TGW was significantly lower than other varieties (Table 6.3.6). All yield components assessed were higher in 2018 compared to 2017 based on both datasets (Table 6.3.5 & Table 6.3.6).

Table 6.3.5. Main effect means, ±SE and p-values for the effects and interactions of management and variety on spelt ears/m^2, grains/m^2, grains/ear and thousand grain weight (TGW).

	Ears/m^2		Grains/m^2		Grains/Ear		TGW (g)	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	232 ± 14.9	24	2803 ± 263.5	24	12.5 ± 1.14	24	45.0 ± 1.16	24
2018	291 ± 23.7	28	4969 ± 393.7	28	17.8 ± 0.75	28	49.8 ± 0.52	28
Management								
Conventional	293 ± 24.4	24	4459 ± 517.0	24	14.7 ± 1.17	24	47.4 ± 1.01	24
Organic	238 ± 17.3	28	3550 ± 276.7	28	15.8 ± 0.98	28	47.8 ± 0.95	28
Variety								
Fild	202 ± 27.9	13	3586 ± 568.8	13	17.9 ± 1.64	13	49.4 ± 1.31 a	13
Ob Rot	282 ± 32.8	13	3946 ± 618.7	13	14.4 ± 1.50	13	49.3 ± 1.12 a	13
Rub	283 ± 24.3	13	3952 ± 483.8	13	13.8 ± 1.21	13	44.3 ± 1.29 b	13
ZOR	288 ± 30.4	13	4393 ± 646.3	13	15.1 ± 1.57	13	47.4 ± 1.38 a	13
ANOVA *p*-values								
Main Effects								
man	**0.043**		**0.036**		NS		NS	
var	NS		NS		NS		**0.008**	
Interactions								
man:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Data from the site Spindlestone were excluded from the analysis. Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVA.

Table 6.3.6. Main effect means, ±SE and p-values for the effects and interactions of management, fertiliser type and variety on spelt ears/m^2, grains/m^2, grains/ear and thousand grain weight (TGW).

	Ears/m^2		Grains/m^2		Grains/Ear		TGW (g)	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	242 ± 13.9	32	2870 ± 252.0	32	12.0 ± 0.88	32	44.4 ± 1.01	32
2018	329 ± 35.1	24	4989 ± 478.5	24	16.2 ± 0.59	24	48.6 ± 0.53	24
Management								
Conventional	311 ± 20.4	40	4333 ± 352.0	40	13.7 ± 0.70	40	46.8 ± 0.79	40
Organic	201 ± 27.8	16	2391 ± 245.8	16	14.1 ± 1.36	16	44.6 ± 1.25	16
Fertiliser Type								
Bio Digestate	301 ± 25.4	28	4232 ± 381.1	28	14.6 ± 0.89	28	46.1 ± 0.90	28
Farm	258 ± 24.6	28	3324 ± 414.0	28	13.0 ± 0.87	28	46.3 ± 1.03	28
Variety								
Fild	221 ± 31.4	14	3414 ± 553.4	14	15.6 ± 1.46	14	47.6 ± 1.44 a	14
Ob Rot	276 ± 33.7	14	3472 ± 488.1	14	13.2 ± 1.31	14	47.9 ± 1.23 a	14
Rub	307 ± 36.4	14	4057 ± 577.2	14	13.3 ± 1.07	14	43.0 ± 1.01 b	14
ZOR	314 ± 38.5	14	4169 ± 682.6	14	13.1 ± 1.16	14	46.3 ± 1.42 a	14
ANOVA *p*-values								
Main Effects								
man	**0.002**		**<0.001**		NS		NS	
ft	NS		**0.049**		NS		NS	
var	NS		NS		NS		**0.032**	
Interactions								
man:ft	NS		NS		NS		NS	
man:var	NS		NS		NS		NS	
ft:var	NS		NS		NS		NS	
man:ft:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

6.3.3 SPAD

Significant main effects of management were detected for SPAD readings at GS39 ($p = 0.002$) and highly significant effects of management were detected at GS47, GS59 and GS75 ($p < 0.001$); SPAD readings were significantly higher under conventional compared with organic management at all growth stages (Table 6.3.7). Significant main effects of variety were detected for SPAD readings at GS39 ($p = 0.005$); Filderstolz SPAD readings were significantly higher than all other varieties (Table 6.3.7). Highly significant main effects of fertiliser type were detected for SPAD readings at GS47 ($p < 0.001$); biogas digestate readings were significantly higher than the farm-based fertility (Table 6.3.8). For farms receiving biogas digestate, management was also significant at all four growth stages ($p < 0.001$), while variety was significant at GS39 ($p < 0.001$), GS47 ($p = 0.011$) and GS59 ($p = 0.005$); SPAD readings were significantly higher under conventional management and Filderstolz had higher SPAD readings than all other varieties at the first three growth stages (Table 6.3.8).

Table 6.3.7. Main effect means, ±SE and p-values for the effects and interactions of management and variety on spelt SPAD readings at four growth stages.

	GS39		GS47		GS59		GS75	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	41.7 ± 0.73	28	41.1 ± 0.95	28	37.5 ± 1.06	28	35.8 ± 1.49	28
2018	39.2 ± 0.81	28	41.6 ± 1.26	28	38.1 ± 1.74	28	34.2 ± 1.81	28
Management								
Conventional	42.3 ± 0.55	24	44.3 ± 1.10	24	42.6 ± 1.36	24	41.8 ± 1.35	24
Organic	39.1 ± 0.82	32	39.2 ± 0.92	32	34.2 ± 1.08	32	29.9 ± 1.11	32
Variety								
Fild	43.4 ± 1.13 a	14	44.1 ± 1.65	14	40.2 ± 2.06	14	36.2 ± 2.34	14
Ob Rot	40.0 ± 0.93 b	14	42.1 ± 1.30	14	38.4 ± 1.84	14	35.2 ± 1.96	14
Rub	39.9 ± 1.12 b	14	39.7 ± 1.40	14	37.0 ± 1.79	14	35.6 ± 2.30	14
ZOR	38.6 ± 1.01 b	14	39.7 ± 1.71	14	35.7 ± 2.37	14	32.9 ± 2.83	14
ANOVA *p*-values								
Main Effects								
man	**0.002**		**<0.001**		**<0.001**		**<0.001**	
var	**0.005**		NS		NS		NS	
Interactions								
man:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVA.

Table 6.3.8. Main effect means, ±SE and p-values for the effects and interactions of management, fertiliser type and variety on spelt SPAD readings at four growth stages.

	GS39		GS47		GS59		GS75	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	40.3 ± 0.58	32	42.5 ± 0.92	32	39.4 ± 1.17	32	38.4 ± 1.54	32
2018	42.6 ± 0.81	24	46.2 ± 1.45	24	45.1 ± 1.20	24	39.8 ± 1.48	24
Management								
Conventional	42.6 ± 0.53	40	46.4 ± 0.84	40	44.0 ± 1.06	40	41.8 ± 1.08	40
Organic	37.8 ± 0.49	16	38.2 ± 1.17	16	36.5 ± 0.92	16	32.1 ± 1.72	16
Fertiliser Type								
Bio Digestate	41.5 ± 0.79	28	46.3 ± 0.94	28	42.8 ± 1.25	28	39.8 ± 1.32	28
Farm	41.0 ± 0.61	28	41.8 ± 1.29	28	40.8 ± 1.35	28	38.2 ± 1.73	28
Variety								
Fild	43.7 ± 1.06 a	14	46.9 ± 1.84 a	14	45.3 ± 1.91 a	14	43.0 ± 2.03	14
Ob Rot	40.7 ± 0.87 bc	14	44.6 ± 1.46 ab	14	42.6 ± 1.28 ab	14	39.5 ± 1.27	14
Rub	41.5 ± 0.96 ab	14	42.2 ± 1.46 b	14	40.4 ± 1.61 b	14	37.4 ± 2.03	14
ZOR	39.1 ± 0.76 c	14	42.7 ± 1.83 ab	14	39.0 ± 2.16 b	14	36.1 ± 2.81	14
ANOVA *p*-values								
Main Effects								
man	**<0.001**		**<0.001**		**<0.001**		**<0.001**	
ft	NS		**<0.001**		NS		NS	
var	**<0.001**		**0.011**		**0.005**		NS	
Interactions								
man:ft	NS		NS		NS		NS	
man:var	NS		NS		NS		NS	
ft:var	NS		NS		NS		NS	
man:ft:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test $p < 0.05$). Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

6.3.4 DISEASE SEVERITY

6.3.4.1 YELLOW RUST

Significant main effects of management were detected for yellow stripe rust (*Puccinia striiformis*) AUDPC on L1 ($p = 0.016$) and L2 ($p < 0.001$); disease severity was significantly higher under organic than conventional management on both leaves (Table 6.3.9). Significant main effects of variety were detected for yellow rust AUDPC on L1 ($p = 0.004$) and highly significant main effects of variety were detected on L2 an L3 ($p < 0.001$); ZOR had significantly higher disease severity on L1, ZOR and Filderstolz had significantly higher severity on L2 and Filderstolz had significant higher yellow rust severity than all other varieties on L3 (Table 6.3.9). On the farms receiving biogas digestate, management was also significant on L1 ($p = 0.016$) and L2 ($p < 0.001$) and variety was significant on L1 ($p = 0.033$) and highly significant on L2 and L3 (p <0.001); yellow rust disease severity was significantly higher in organic systems and ZOR and Filderstolz had the highest disease severity among varieties (Table 6.3.10). Fertiliser type did not have a significant effect on yellow rust severity (Table 6.3.10), while yellow rust disease levels were higher in 2018 compared to 2017 based on both datasets (Table 6.3.9 &Table 6.3.10).

Table 6.3.9. Main effect means, ±SE and *p*-values for the effects and interactions of management and variety on the Area Under Disease Progress Curve (AUDPC) for yellow stripe rust (*Puccinia striiformis*) on spelt leaves.

	Leaf 1		**Leaf 2**		**Leaf 3**		**Leaf 4**	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	88 ± 25.8	28	185 ± 34.9	28	413 ± 59.5	28	488 ± 107.2	28
2018	69 ± 17.1	28	123 ± 28.2	28	198 ± 50.1	28	200 ± 42.4	28
Management								
Conventional	39 ± 26.7	24	65 ± 23.1	24	308 ± 79.3	24	256 ± 71.4	24
Organic	108 ± 16.6	32	221 ± 30.9	32	304 ± 41.9	32	410 ± 90.2	32
Variety								
Fild	59 ± 14.9 b	14	216 ± 47.1 a	14	617 ± 114.9 a	14	619 ± 169.6	14
Ob Rot	44 ± 18.3 b	14	68 ± 23.5 b	14	130 ± 28.5 b	14	228 ± 42.8	14
Rub	41 ± 10.9 b	14	82 ± 20.3 b	14	218 ± 37.2 b	14	280 ± 52.1	14
ZOR	169 ± 49.7 a	14	250 ± 59.1 a	14	257 ± 51.6 b	14	249 ± 142.9	14
ANOVA *p*-values								
Main Effects								
man	**0.002**		**<0.001**		NS		NS	
var	**0.004**		**<0.001**		**<0.001**		NS	
Interactions								
man:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVA.

Table 6.3.10. Main effect means, ±SE and *p*-values for the effects and interactions of management, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for yellow stripe rust (*Puccinia striiformis*) on spelt leaves.

	Leaf 1		Leaf 2		Leaf 3		Leaf 4	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	102 ± 25.2	32	143 ± 21.6	32	408 ± 58.3	32	335 ± 61.4	32
2018	55 ± 17.9	24	82 ± 22.1	24	216 ± 56.1	24	206 ± 44.7	24
Management								
Conventional	52 ± 19.4	40	84 ± 17.2	40	354 ± 57.0	40	293 ± 52.2	40
Organic	157 ± 22.8	16	200 ± 26.6	16	257 ± 43.1	16	246 ± 57.3	16
Fertiliser Type								
Bio Digestate	92 ± 21.2	28	130 ± 22.4	28	318 ± 54.8	28	256 ± 48.8	28
Farm	71 ± 25.5	28	104 ± 22.9	28	334 ± 66.5	28	303 ± 65.4	28
Variety								
Fild	69 ± 19.2 b	14	168 ± 31.8 a	14	726 ± 98.7 a	14	423 ± 131.3	14
Ob Rot	47 ± 17.3 b	14	52 ± 15.4 b	14	104 ± 17.6 c	14	186 ± 24.7	14
Rub	48 ± 14.2 b	14	73 ± 17.8 b	14	215 ± 29.4 bc	14	347 ± 62.0	14
ZOR	162 ± 55.2 a	14	175 ± 42.6 a	14	259 ± 50.2 b	14	161 ± 49.4	14
ANOVA *p*-values								
Main Effects								
man	**0.002**		**<0.001**		NS		NS	
ft	NS		NS		NS		NS	
var	**0.033**		**<0.001**		**<0.001**		NS	
Interactions								
man:ft	NS		NS		NS		NS	
man:var	NS		NS		NS		NS	
ft:var	NS		NS		NS		**0.026**	
man:ft:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

6.3.4.2 LEAF BLOTCH

Septoria leaf blotch (*Septoria tritici)* was present during the growing season but AUDPC was less than 5.0 across all varieties and treatments, therefore means tables are not presented.

6.3.4.3 POWDERY MILDEW

Significant main effects of variety were detected for powdery mildew (*Blumeria graminis*) AUDPC on L2 (p = *0*.048); Rubiota had significantly higher disease severity on L2 than all other varieties (Table 6.3.11). Significant main effects of fertiliser type were detected for powdery mildew AUDPC on L4 (p = *0*.023); spelt plants fertilised with biogas digestate had significantly higher levels of powdery mildew than those with on-farm fertiliser treatments (Table 6.3.12). For farms receiving biogas digestate, variety was significant on L3 (p = *0*.036) and L4 (p = 0.018); powdery mildew disease severity was significantly higher for Rubiota compared to all other varieties (Table 6.3.12).

Table 6.3.11. Main effect means, ±SE and *p*-values for the effects and interactions of management and variety on the Area Under Disease Progress Curve (AUDPC) for powdery mildew (*Blumeria graminis*) on spelt leaves.

	Leaf 1		Leaf 2		Leaf 3		Leaf 4	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	0 ± 0.1	28	5 ± 2.8	28	22 ± 14.0	28	51 ± 25.3	28
2018	0 ± 0.0	28	3 ± 2.1	28	1 ± 0.6	28	3 ± 3.3	28
Management								
Conventional	0 ± 0.0	24	3 ± 2.4	24	1 ± 0.7	24	4 ± 3.9	24
Organic	0 ± 0.0	32	5 ± 2.5	32	19 ± 12.3	32	45 ± 22.3	32
Variety								
Fild	0 ± 0.0	14	0 ± 0.2 b	14	1 ± 0.5	14	9 ± 8.6	14
Ob Rot	0 ± 0.0	14	2 ± 1.0 b	14	5 ± 3.1	14	22 ± 12.9	14
Rub	0 ± 0.1	14	13 ± 6.5 a	14	39 ± 27.5	14	71 ± 49.1	14
ZOR	0 ± 0.1	14	1 ± 0.9 b	14	1 ± 1.3	14	7 ± 4.7	14
ANOVA *p*-values								
Main Effects								
man	NS		NS		NS		NS	
var	NS		**0.048**		NS		NS	
Interactions								
man:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVA.

Table 6.3.12. Main effect means, ±SE and *p*-values for the effects and interactions of management, fertiliser type and variety on the Area Under Disease Progress Curve (AUDPC) for powdery mildew (*Blumeria graminis*) on spelt leaves.

	Leaf 1		Leaf 2		Leaf 3		Leaf 4	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	0 ± 0.0	32	0 ± 0.0	32	1 ± 0.5	32	7 ± 3.8	32
2018	0 ± 0.2	24	3 ± 2.4	24	0 ± 0.3	24	2 ± 1.6	24
Management								
Conventional	0 ± 0.1	40	2 ± 1.5	40	1 ± 0.3	40	4 ± 1.9	40
Organic	0 ± 0.0	16	0 ± 0.0	16	1 ± 0.7	16	7 ± 6.5	16
Fertiliser Type								
Bio Digestate	0 ± 0.2	28	0 ± 0.3	28	1 ± 0.5	28	9 ± 4.4	28
Farm	0 ± 0.0	28	2 ± 2.1	28	0 ± 0.2	28	0 ± 0.0	28
Variety								
Fild	0 ± 0.0	14	0 ± 0.0	14	0 ± 0.0 b	14	0 ± 0.1 b	14
Ob Rot	0 ± 0.0	14	0 ± 0.4	14	0 ± 0.0 b	14	0 ± 0.0 b	14
Rub	0 ± 0.1	14	4 ± 4.2	14	2 ± 1.0 a	14	16 ± 8.2 a	14
ZOR	0 ± 0.4	14	1 ± 0.5	14	1 ± 0.5 b	14	3 ± 2.5 b	14
ANOVA *p*-values								
Main Effects								
man	NS		NS		NS		NS	
ft	NS		NS		NS		**0.023**	
var	NS		NS		**0.036**		**0.018**	
Interactions								
man:ft	NS		NS		NS		NS	
man:var	NS		NS		NS		NS	
ft:var	NS		NS		NS		**0.018**	
man:ft:var	NS		NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test *p* <0.05). Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

6.3.4.4 EAR DISEASE

There were no significant main or interaction effects for management, fertility or variety on the presence of ergot (*Claviceps purpurea*) on spelt ears; ergot was present at higher levels in 2017 compared to 2018 (Table 6.3.13& Table 6.3.14). Yellow rust (*Puccinia striiformis*) was present in spelt ears prior to harvest but percentage cover was less than 0.02 across all varieties and treatments, therefore means tables are not presented.

Table 6.3.13. Main effect means, ±SE and *p*-values for the effects and interactions of management and variety on percentage disease cover for ergot (*Claviceps purpurea*) on spelt ears.

	% Disease Cover	
Year	**mean ± SE**	**n**
2017	2.25 ± 0.329	28
2018	0.89 ± 0.201	28
Management		
Conventional	1.67 ± 0.269	24
Organic	1.49 ± 0.314	32
Variety		
Fild	1.45 ± 0.423	14
Ob Rot	1.66 ± 0.455	14
Rub	1.37 ± 0.427	14
ZOR	1.79 ± 0.428	14
ANOVA *p*-values		
Main Effects		
man	NS	
var	NS	
Interactions		
man:var	NS	

Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVA

Table 6.3.14. Main effect means, ±SE and *p*-values for the effects and interactions of management, fertiliser type and variety on percentage disease cover for ergot (*Claviceps purpurea*) on spelt ears

	% Disease Cover	
Year	**mean ± SE**	**n**
2017	3.21 ± 0.448	32
2018	1.18 ± 0.242	24
Management		
Conventional	2.60 ± 0.364	40
Organic	1.69 ± 0.548	16
Fertiliser Type		
Bio Digestate	2.79 ± 0.542	28
Farm	1.89 ± 0.269	28
Variety		
Fild	1.69 ± 0.391	14
Ob Rot	2.43 ± 0.683	14
Rub	1.79 ± 0.390	14
ZOR	3.44 ± 0.814	14
ANOVA *p*-values		
Main Effects		
man	NS	
ft	NS	
var	NS	
Interactions		
man:ft	NS	
man:var	NS	
ft:var	NS	
man:ft:var	NS	

Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

6.3.5 GRAIN MILLING QUALITY

6.3.5.1 SPECIFIC WEIGHT

Significant main effects of management ($p = 0.019$) and variety ($p = 0.024$) were detected for spelt grain specific weight, which was was significantly higher under organic management than conventional management and ZOR had significantly higher specific weight than all other varieties except Rubiota (Table 6.3.15). On the farms receiving biogas digestate, variety was significant for spelt specific weight ($p = 0.004$); ZOR had significantly higher specific weight than all other varieties (Table 6.3.16).

6.3.5.2 PROTEIN CONTENT

Significant main effects of management ($p = 0.029$) and variety ($p = 0.048$) were detected for spelt grain protein content, which was significantly higher under conventional management than organic management and Oberkulmer Rotkorn and Rubiota had the highest while Filderstolz had the lowest protein content (Table 6.3.15). On the farms receiving biogas digestate, management and variety were highly significant for spelt protein content (p <0.001); protein was significantly higher under conventional management and Oberkulmer Rotkorn and Rubiota had significantly higher protein content compared to ZOR and Filderstolz (Table 6.3.16).

6.3.5.3 HAGBERG FALLING NUMBER

Management, fertiliser type and variety did not have significant effects on HFN, but HFN was higher in 2017 compared to 2018 based on both datasets (Table 6.3.15 & Table 6.3.16).

In 2017, Rubiota had the highest HFN and ZOR the lowest; in 2018, Filderstolz had the highest HFN and Oberkulmer Rotkorn the lowest (Table 6.3.17).

Hagberg Falling Number was highest at Quarry field in 2017 and at Applebys Whin and Tughall in 2018; the lowest HFNs were at Spindlestone in 2017and Moorhouse and Pawson in 2018 (Table 6.3.18).

Table 6.3.15. Main effect means, ±SE and *p*-values for the effects and interactions of management and variety on specific weight, protein content and Hagberg Falling Number (HFN) of spelt grain.

	Specific Weight (kg/hl)		Protein (%)		HFN (s)	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	78.7 ± 0.36	24	14.3 ± 0.37	24	321 ± 12.5	24
2018	77.4 ± 0.34	28	14.0 ± 0.36	28	167 ± 15.7	28
Management						
Conventional	77.5 ± 0.48	24	14.7 ± 0.42	24	234 ± 26.7	24
Organic	78.5 ± 0.24	28	13.6 ± 0.29	28	242 ± 15.6	28
Variety						
Fild	77.7 ± 0.41 b	13	13.3 ± 0.31 c	13	256 ± 23.4	13
Ob Rot	77.2 ± 0.56 b	13	14.9 ± 0.62 a	13	216 ± 31.0	13
Rub	78.0 ± 0.44 ab	13	14.8 ± 0.59 ab	13	262 ± 36.9	13
ZOR	79.1 ± 0.58 a	13	13.5 ± 0.36 bc	13	219 ± 26.3	13
ANOVA *p*-values						
Main Effects						
man	**0.019**		**0.029**		NS	
var	**0.024**		**0.048**		NS	
Interactions						
man:var	NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test p <0.05). Data from the site Spindlestone were excluded from the analysis. Biogas digestate treatments were not included in the analysis and Year was not included as a fixed-factor in the ANOVA.

Table 6.3.16. Means, ±SE and *p*-values for the effects and interactions of management, fertiliser type and variety on specific weight, protein content and Hagberg Falling Number (HFN) of spelt grain.

	Specific Weight (kg/hl)		**Protein (%)**		**HFN (s)**	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	78.4 ± 0.35	32	14.4 ± 0.35	32	321 ± 10.6	32
2018	76.9 ± 0.46	24	15.1 ± 0.49	24	117 ± 12.4	24
Management						
Conventional	77.6 ± 0.39	40	15.4 ± 0.34	40	239 ± 21.7	40
Organic	78.3 ± 0.35	16	13.0 ± 0.18	16	222 ± 11.0	16
Fertiliser Type						
Bio Digestate	77.6 ± 0.42	28	15.1 ± 0.44	28	238 ± 21.8	28
Farm	78.0 ± 0.42	28	14.4 ± 0.37	28	230 ± 23.1	28
Variety						
Fild	77.0 ± 0.55 b	14	13.6 ± 0.37 b	14	245 ± 28.1	14
Ob Rot	77.0 ± 0.61 b	14	15.9 ± 0.59 a	14	216 ± 33.8	14
Rub	77.6 ± 0.47 b	14	15.9 ± 0.61 a	14	245 ± 36.7	14
ZOR	79.5 ± 0.51 a	14	13.6 ± 0.37 b	14	229 ± 29.7	14
ANOVA *p*-values						
Main Effects						
man	NS		**<0.001**		NS	
ft	NS		NS		NS	
var	**0.004**		**<0.001**		NS	
Interactions						
man:ft	NS		NS		NS	
man:var	NS		NS		NS	
ft:var	NS		NS		NS	
man:ft:var	NS		NS		NS	

Means labelled with the same letter within the same column are not significantly different (Tukey's Honestly Significant Difference test *p* <0.05). Only sites applying biogas digestate were included in the analysis. Year was not included as a fixed-factor in the ANOVA.

Table 6.3.17. Interaction means ±SE for the effects of trial year and variety on spelt Hagberg Falling Number.

	Hagberg Falling Number (s)			
	Filderstolz	**Ob Rotkorn**	**Rubiota**	**ZOR**
2017	323 ± 14.5	303 ± 27.1	360 ± 35.4	298 ± 14.9
2018	199 ± 26.2	142 ± 32.6	178 ± 40.4	151 ± 27.1

Data from the site Spindlestone were excluded from the analysis. Biogas digestate treatments were not included in the analysis

Table 6.3.18. Means, ±SE, for the effects of year and site on spelt Hagberg Falling Number.

	Hagberg Falling Number (s)	
	mean ± SE	**n**
2017		
Gibside	348 ± 28.4	4
Gilchesters 1	244 ± 13.2	4
Moorhouse	296 ± 24.4	4
Newlands	337 ± 24.3	4
Quarry	388 ± 19.1	4
Spindlestone	156 ± 13.4	4
Wheldon	312 ± 25.8	4
2018		
Applebys Whin	255 ± 21.1	4
Gilchesters 2	180 ± 26.5	4
Moorhouse	75 ± 5.3	4
Pawson	80 ± 15.4	4
Three Corners	215 ± 27.2	4
Tughall	248 ± 21.1	4
Wheldon	119 ± 36.4	4

Biogas digestate treatments were not included in the analysis

6.4 RYE RESULTS

6.4.1 GRAIN HARVEST

6.4.1.1 GRAIN YIELD

Rye grain yield was higher in 2018 than 2017, conventional management produced higher yields than organic management and plots treated with biogas digestate yielded more than those without (Table 6.4.1). Dankowksie Amber and Elias were the highest yielding varieties while Schlaegler was the lowest (Table 6.4.1).

Elias and Dankowskie Amber were the highest yielding rye varieties in both trial years; Elvi was the lowest yielding in 2017 and Schlaegler yielded the least in 2018 (Table 6.4.2).

Grain yields were highest at Newlands, Gibside and Quarry in 2017 and at Moorhouse and Pawson in 2018; Spindlestone was the lowest yielding site in 2017 and Applebys Whin was the lowest yielding in 2018 (Table 6.4.3).

6.4.1.2 PLANT HEIGHT

Rye plants were taller in 2018 than 2017 but did not differ between management systems or fertiliser types (Table 6.4.1). Dankowskie Amber was the shortest variety while Schlaegler was the tallest (Table 6.4.1).

6.4.1.3 HARVEST INDEX

Rye harvest index was higher in 2018 than 2017 but did not differ between management systems or fertiliser types (Table 6.4.1). Schlaegler had the lowest HI of all rye varieties (Table 6.4.1).

6.4.1.4 LODGING SEVERITY

Lodging severity in rye was higher in 2018 than 2017 and under conventional compared to organic management but did not differ substantially in response to fertiliser type (Table 6.4.1). Lodging severity was highest in the variety Schlaegler and lowest in Dankowskie Amber (Table 6.4.1).

In 2017, Quarry field was the only site with recorded lodging while in 2018, Moorhouse and Pawson had the highest lodging severity, though all sites experienced lodging (Table 6.4.3).

Table 6.4.1. Means, ±SE, for the effects of year, management system, fertiliser type and variety on rye yield, plant height, harvest index (HI) and lodging severity.

	Grain Yield (t/ha)		**Plant Height (cm)**		**HI %**		**Lodging Severity**$^{+}$	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	2.24 ± 0.179	25	133 ± 2.3	29	40.7 ± 1.14	25	0.66 ± 0.369	29
2018	4.09 ± 0.379	25	154 ± 3.7	25	44.4 ± 0.82	25	4.00 ± 0.707	25
Management								
Conventional	3.69 ± 0.314	32	142 ± 3.4	32	42.6 ± 1.08	32	3.22 ± 0.636	32
Organic	2.23 ± 0.289	18	143 ± 3.7	22	42.4 ± 0.83	18	0.73 ± 0.412	22
Fertiliser Type								
Bio Digestate	3.70 ± 0.349	20	143 ± 3.4	20	42.2 ± 1.30	20	2.25 ± 0.732	20
Farm	2.80 ± 0.325	30	143 ± 3.4	34	42.7 ± 0.91	30	2.18 ± 0.564	34
Variety								
Dank	3.69 ± 0.458	12	132 ± 3.7	13	44.7 ± 1.00	12	0.31 ± 0.208	13
Elias	3.76 ± 0.655	13	142 ± 3.8	14	44.7 ± 1.14	13	2.71 ± 1.019	14
Elvi	2.78 ± 0.400	12	142 ± 5.0	13	44.0 ± 1.19	12	1.08 ± 0.487	13
Sch	2.43 ± 0.316	13	155 ± 5.5	14	37.1 ± 1.42	13	4.50 ± 1.015	14

$^{+}$Lodging severity is measured on a 0-9 scale (0=upright; 9=flat).
Data from the site Spindlestone were excluded from the grain yield and HI analyses.

Table 6.4.2. Interaction means ±SE for the effects of trial year and variety on rye grain yield.

	Grain Yield (t/ha)			
	Dankowskie	**Elias**	**Elvi**	**Schlaegler**
2017	2.59 ± 0.345	2.66 ± 0.409	1.76 ± 0.350	1.90 ± 0.226
2018	5.23 ± 0.341	4.71 ± 1.073	3.80 ± 0.407	2.89 ± 0.508

Data from the site Spindlestone were excluded from the analysis.

Table 6.4.3. Means, ±SE, for the effects of year and site on rye grain yield and lodging severity.

	Grain Yield (t/ha)		**Lodging Severity**$^{+}$	
Site	**mean ± SE**	**n**	**mean ± SE**	**n**
		2017		
Gibside	2.44 ± 0.233	8	0.00 ± 0.000	8
Gilchesters 1	1.88 ± 0.315	8	0.00 ± 0.000	8
Newlands	3.27 ± NA	1	0.00 ± NA	1
Quarry	2.27 ± 0.381	8	2.38 ± 1.179	8
Spindlestone	0.45 ± 0.067	4	0.00 ± 0.000	4
		2018		
Applebys Whin	0.46 ± 0.106	2	2.00 ± 2.000	2
Moorhouse	5.67 ± 0.521	8	4.75 ± 1.320	8
Pawson	4.37 ± 0.381	8	5.75 ± 1.098	8
Tughall	2.42 ± 0.578	3	1.67 ± 1.667	3
Wheldon	3.40 ± 0.608	4	1.75 ± 1.750	4

$^{+}$Lodging severity is measured on a 0-9 scale (0=upright; 9=flat).

6.4.2 YIELD COMPONENTS

Rye ear number and grains/m^2 were higher in 2018 than 2017, in conventional systems compared to organic systems and when biogas digestate was applied compared to farm-based fertility (Table 6.4.4). Dankowskie Amber had the highest ear number and grains/m^2 of all varieties while Elvi had the lowest ears/m^2 and Schlaegler the lowest grains/m^2 (Table 6.4.4).

Rye thousand grain weight did not differ between years, management or fertiliser type. Schlaegler had the lowest TGW of all varieties and Elias had the highest (Table 6.4.4).

Table 6.4.4. Means, ±SE, for the effects of year, management system, fertiliser type and variety on rye ears/m^2, grains/m^2, grains/ear and thousand grain weight (TGW).

	Ears/m^2		Grains/m^2		Grains/ear		TGW (g)	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	222 ± 17.9	25	8714 ± 580.1	25	42.0 ± 2.52	25	36.6 ± 0.86	25
2018	317 ± 22.8	25	15350 ± 1308.8	25	47.8 ± 1.52	25	37.3 ± 0.87	25
Management								
Conventional	301 ± 19.9	32	13672 ± 1176.7	32	45.5 ± 2.18	32	37.5 ± 0.69	32
Organic	214 ± 21.1	18	9117 ± 740.2	18	43.9 ± 1.69	18	36.0 ± 1.15	18
Fertiliser Type								
Bio Digestate	337 ± 21.0	20	14576 ± 1557.0	20	42.7 ± 2.88	20	36.8 ± 0.82	20
Farm	224 ± 18.4	30	10336 ± 859.9	30	46.4 ± 1.63	30	37.1 ± 0.86	30
Variety								
Dank	309 ± 29.1	12	14003 ± 2179.6	12	44.2 ± 3.51	12	38.7 ± 1.10	12
Elias	276 ± 35.9	13	12245 ± 1712.2	13	44.8 ± 2.50	13	39.5 ± 0.94	13
Elvi	232 ± 28.7	12	11602 ± 1328.1	12	51.5 ± 2.56	12	37.0 ± 0.98	12
Sch	262 ± 31.9	13	10397 ± 1558.1	13	39.6 ± 2.85	13	32.8 ± 0.91	13

Data from the site Spindlestone were excluded from the analysis.

6.4.3 SPAD

SPAD readings were higher in conventional systems compared to organic systems and with biogas digestate compared to farm-based fertility across all four growth stages (Table 6.4.5). SPAD readings did not differ substantially by variety at GS49 or GS59 but at GS69 and GS79, readings for Dankowskie Amber and Elvi were higher than those of Elias and Schlaegler (Table 6.4.5).

Table 6.4.5. Means, ±SE, for the effects of year, management system, fertiliser type and variety on rye SPAD readings at four growth stages.

	GS49		GS59		GS69		GS79	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	37.9 ± 0.51	29	38.1 ± 0.81	29	35.3 ± 1.41	29	33.1 ± 1.63	29
2018	40.1 ± 0.86	25	42.4 ± 1.28	25	39.6 ± 1.42	25	33.7 ± 1.73	25
Management								
Conventional	40.8 ± 0.51	32	42.3 ± 0.98	32	41.4 ± 1.10	32	38.2 ± 1.10	32
Organic	36.2 ± 0.66	22	36.8 ± 0.94	22	31.4 ± 1.12	22	26.4 ± 1.41	22
Fertiliser Type								
Bio Digestate	39.5 ± 0.75	20	41.8 ± 1.01	20	41.0 ± 1.14	20	37.7 ± 1.37	20
Farm	38.6 ± 0.67	34	39.1 ± 1.07	34	35.1 ± 1.38	34	30.8 ± 1.54	34
Variety								
Dank	38.8 ± 0.91	13	39.7 ± 1.52	13	38.1 ± 2.65	13	35.1 ± 2.71	13
Elias	39.7 ± 1.26	14	40.7 ± 1.61	14	36.3 ± 1.90	14	31.8 ± 2.29	14
Elvi	39.8 ± 0.91	13	41.8 ± 1.94	13	38.8 ± 2.16	13	35.8 ± 2.14	13
Sch	37.4 ± 0.83	14	38.2 ± 1.15	14	36.1 ± 1.68	14	31.2 ± 2.24	14

6.4.4 DISEASE SEVERITY

6.4.4.1 **BROWN RUST**

Brown leaf rust (*Puccinia recondite*) AUDPC was higher in 2018 compared to 2017 on all four plant leaves while rust severity was higher with conventional management and farm-based fertility on L1 and L2 and higher with organic management and biogas digestate fertility on L3 and L4 (Table 6.4.6). Dankowskie Amber had the lowest brown rust disease severity among all varieties while Elvi had the highest disease severity on all four leaves, including L3, for which Schlaegler also had the highest levels of brown rust disease (Table 6.4.6).

Table 6.4.6. Means, ±SE, for the effects of year, management system, fertiliser type and variety on Area Under Disease Progress Curve (AUDPC) for brown leaf rust (*Puccinia recondita*) on rye leaves.

	Leaf 1		**Leaf 2**		**Leaf 3**		**Leaf 4**	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	10 ± 2.8	29	22 ± 6.9	29	56 ± 16.2	29	59 ± 16.0	29
2018	245 ± 54.6	25	434 ± 90.6	25	526 ± 66.0	25	392 ± 79.9	25
Management								
Conventional	88 ± 24.4	32	145 ± 31.9	32	298 ± 59.8	32	279 ± 66.7	32
Organic	164 ± 63.6	22	312 ± 112.7	22	238 ± 69.1	22	117 ± 40.9	22
Fertiliser Type								
Bio Digestate	75 ± 28.4	20	135 ± 40.5	20	287 ± 79.7	20	282 ± 96.4	20
Farm	145 ± 44.0	34	258 ± 75.7	34	266 ± 54.8	34	172 ± 40.6	34
Variety								
Dank	25 ± 13	13	53 ± 28.4	13	74 ± 27.6	13	74 ± 27.7	13
Elias	78 ± 30.4	14	138 ± 57.0	14	192 ± 52.5	14	113 ± 34.6	14
Elvi	246 ± 93.4	13	347 ± 137.6	13	428 ± 119.8	13	420 ± 144.8	13
Sch	130 ± 58.8	14	311 ± 124.0	14	399 ± 99.3	14	249 ± 72.3	14

6.4.4.2 **POWDERY MILDEW**

Powdery mildew (*Blumeria graminis*) AUDPC was higher in 2018 compared to 2017 on all four plant leaves while mildew severity was higher with conventional management and farm-based fertility on L1 and L2 and higher with organic management and biogas digestate fertility on L3 and L4 (Table 6.4.7). Elias had the highest powdery mildew disease severity on L1 and L2 and Schlaegler had the highest mildew severity on L3 and L4 (Table 6.4.7).

Table 6.4.7. Means, ±SE, for the effects of year, management system, fertiliser type and variety on Area Under Disease Progress Curve (AUDPC) for powdery mildew (*Blumeria graminis*) on rye leaves.

	Leaf 1		**Leaf 2**		**Leaf 3**		**Leaf 4**	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	0 ± 0.4	29	2 ± 0.9	29	5 ± 1.7	29	4 ± 2.5	29
2018	18 ± 8.8	25	44 ± 15.1	25	106 ± 27.1	25	104 ± 30.6	25
Management								
Conventional	2 ± 0.7	32	12 ± 5.2	32	59 ± 19.8	32	80 ± 25.2	32
Organic	18 ± 10.1	22	35 ± 16.7	22	41 ± 20.1	22	7 ± 3.4	22
Fertiliser Type								
Bio Digestate	2 ± 0.7	20	6 ± 3.3	20	57 ± 27.5	20	67 ± 30.7	20
Farm	13 ± 6.6	34	30 ± 11.6	34	48 ± 16.1	34	41 ± 17.3	34
Variety								
Dank	11 ± 9.9	13	14 ± 13.9	13	20 ± 16.9	13	5 ± 3.3	13
Elias	15 ± 13.3	14	32 ± 21.6	14	66 ± 33.1	14	35 ± 19.0	14
Elvi	4 ± 2.7	13	15 ± 11.5	13	33 ± 13.2	13	60 ± 30.8	13
Sch	4 ± 2.2	14	23 ± 11.3	14	83 ± 38.8	14	100 ± 48.1	14

6.4.4.3 EAR DISEASE

Percent disease cover of ergot (*Claviceps purpurea*) on rye grains was higher in 2017 than 2018 but did not differ substantially by management system or fertiliser type (Table 6.4.8). Elvi and Schlaegler had higher ergot disease cover than the other rye varieties (Table 6.4.8).

Table 6.4.8. Means, ±SE for the effects of year, management system, fertiliser type and variety on percentage disease cover for ergot (*Claviceps purpurea*) on rye ears.

	% Disease Cover	
Year	**mean ± SE**	**n**
2017	3.02 ± 0.351	29
2018	2.24 ± 0.270	25
Management		
Conventional	2.59 ± 0.301	32
Organic	2.77 ± 0.365	22
Fertiliser Type		
Bio Digestate	2.56 ± 0.255	20
Farm	2.72 ± 0.337	34
Variety		
Dank	2.36 ± 0.422	13
Elias	2.37 ± 0.319	14
Elvi	2.98 ± 0.707	13
Sch	2.94 ± 0.356	14

6.4.5 GRAIN MILLING QUALITY

6.4.5.1 SPECIFIC WEIGHT

Rye specific weight did not differ substantially by year, management system or fertiliser type but was slightly higher in 2018 compared to 2017 (Table 6.4.9). Schlaegler had the lowest specific weight of all varieties while Dankowskie Amber and Elias had the highest (Table 6.4.9).

6.4.5.2 PROTEIN CONTENT

Rye protein content did not differ substantially by year, management system or fertiliser type while Schlaegler had the highest and Elias had the lowest protein content between varieties (Table 6.4.9).

6.4.5.3 HAGBERG FALLING NUMBER

Rye Hagberg Falling Number was higher in 2017 compared to 2018, in conventional compared to organic systems and with biogas digestate compared to farm-based fertility applications

(Table 6.4.9). Dankowskie Amber and Elias had the highest HFN and Elvi and Schlaegler had the lowest HFN by variety (Table 6.4.9).

In both 2017 and 2018, the varieties with highest HFN were Elias (146 and 93 seconds) and Dankowskie Amber (143 and 90 seconds) and the lowest were Elvi (102 and 71 seconds) and Schlaegler (114 and 69 seconds) (Table 6.4.10).

Hagberg Falling Number was highest at Gibside in 2017 and at Wheldon in 2018; the lowest HFNs were at Spindlestone in 2017and Moorhouse and Pawson in 2018 (Table 6.4.11).

Table 6.4.9. Means, ±SE, for the effects of year, management system, fertiliser type and variety on specific weight, protein content and Hagberg Falling Number (HFN) of rye grain.

	Specific Weight (kg/hl)		**Protein (%)**		**HFN (s)**	
Year	**mean ± SE**	**n**	**mean ± SE**	**n**	**mean ± SE**	**n**
2017	68.5 ± 0.52	25	11.3 ± 0.37	25	127 ± 10.7	25
2018	70.2 ± 0.43	25	11.4 ± 0.25	25	81 ± 4.6	25
Management						
Conventional	69.5 ± 0.50	32	11.9 ± 0.28	32	107 ± 9.5	32
Organic	69.2 ± 0.47	18	10.4 ± 0.25	18	98 ± 7.6	18
Fertiliser Type						
Bio Digestate	69.3 ± 0.58	20	11.7 ± 0.31	20	103 ± 11.2	20
Farm	69.4 ± 0.47	30	11.1 ± 0.30	30	105 ± 8.3	30
Variety						
Dank	70.6 ± 0.57	12	11.2 ± 0.52	12	121 ± 13.2	12
Elias	71.0 ± 0.54	13	10.7 ± 0.34	13	118 ± 14.1	13
Elvi	69.0 ± 0.70	12	11.3 ± 0.45	12	87 ± 10.8	12
Sch	66.9 ± 0.44	13	12.2 ± 0.40	13	90 ± 13.0	13

Data from the site Spindlestone were excluded from the analysis.

Table 6.4.10. Interaction means ±SE for the effects of trial year and variety on rye Hagberg Falling Number.

	Hagberg Falling Number (s)			
	Dankowskie	**Elias**	**Elvi**	**Schlaegler**
2017	143 ± 18.1	146 ± 22.2	102 ± 19.8	114 ± 25.5
2018	90 ± 6.8	93 ± 13.3	71 ± 4.7	69 ± 3.6

Data from the site Spindlestone were excluded from the analysis.

Table 6.4.11. Means, ±SE, for the effects of year and site on rye Hagberg Falling Number.

	Hagberg Falling Number (s)	
	mean ± SE	**n**
2017		
Gibside	185 ± 6.2	8
Gilchesters 1	94 ± 12.4	8
Newlands	137 ± NA	1
Quarry	100 ± 17.3	8
Spindlestone	64 ± 1.5	4
2018		
Applebys Whin	79 ± 2.0	2
Moorhouse	71 ± 2.7	8
Pawson	72 ± 4.0	8
Tughall	89 ± 13.6	3
Wheldon	112 ± 19.4	4

6.5 SPELT DISCUSSION

6.5.1 GRAIN HARVEST

6.5.1.1 GRAIN YIELD

Spelt grain yield was higher in 2018 compared to 2017, whether or not biogas digestate was applied as a fertiliser treatment. This does not follow similar yield patterns for cereals in the UK over the same time period, as wheat yield was 5% lower in 2018 compared to 2017 (DEFRA, 2018a). In the Farmer Participatory trial, spelt yield was 30% lower in 2017 (2.13 t/ha) compared to 2018 (3.05 t/ha) without biogas digestate and 40% lower in 2017 (2.01 t/ha) compared to 2018 (3.34 t/ha) on farms with digestate as an experimental fertiliser.

Considering spelt yields at each site over both trial years, yields are higher in 2018 compared to 2017, but there is also a great deal of variability between locations. Yield variation by environment is expected in crop trials and have been recorded in spelt grown at different sites in Italy (Castagna *et al.*, 1996) and Switzerland (Rüegger and Winzeler, 1993). Spelt yield was highest at Wheldon (2.91 t/ha), Moorhouse (2.63 t/ha) and Newlands (2.59 t/ha) in 2017, all of which were much lower than the highest yields in 2018 at Pawson (4.52 t/ha), Three-Corners (4.25 t/ha) and Moorhouse (4.04 t/ha). The lowest yielding sites were Spindlestone (0.42 t/ha), Quarry (1.11 t/ha) and Gilchesters 1 (1.21 t/ha) in 2017 and Applebys Whin (0.84 t/ha) and Gilchesters 2 (1.38 t/ha) in 2018. As noted previously, Spindlestone was harvested on 27 October due to combine failure, which was one to two months later than all other FPT sites (Table 6.2.4). The delay contributed massive yield losses and yield-related data was not included in analyses for this reason. The site Applebys Whin also had exceptionally low yields, which was likely due to late sowing in that trial year (sown 1 November 2017), resulting in poor establishment.

Yield differences in 2018 throughout the UK are attributed to weather variability, with a cold spring (including late snow from a storm called the “Beast from the East”), high rainfall and a dry, long summer with high temperatures resulting in significant yield variation throughout the country (DEFRA, 2018a). Radiation likely played a role in annual yield differences in the FPT, especially considering how much sun was available during key photosynthesising months of spring and summer. In Northeast England, 2018 had 3.4% more sunshine hours annually and 22%, 23% and 28% more sunshine hours than 2017 over May, June and July respectively (MetOffice, 2018b). Based on field station weather data collected at Nafferton farm, total radiation was higher over the full year of the 2018 trial, particularly over April, May, June and July, which had 1784 MJ/m^2 in 2017 compared to 2018 MJ/m^2 in 2018 (Table A.3., Appendix A). Rainfall was also higher in the second trial year, both regionally and locally. Total annual rainfall in Northeast England was 6% higher in 2018 and 61% higher in April compared to 2017 (MetOffice, 2018b), while total rainfall recorded at Nafferton farm was 674mm in 2017 and 751mm in 2018 (Table A.3., Appendix A). It is worth noting that the annual difference in rainfall was impacted by heavy snow in late winter in 2018, while the summer months were comparatively dry in 2018 compared with 2017. Spelt yields can be negatively affected by lower temperatures and higher than average precipitation (Turinek *et al.*, 2010; Pospišil *et al.*, 2011; Bavec *et al.*, 2012). However, average annual rainfall in Northeast England is 600-1000mm (MetOffice, 2016), therefore both trial years were not unusual in terms of precipitation.

Spelt grain yield was significantly higher on conventional farms (3.15 t/ha) compared to organic farms (2.18 t/ha). Spelt yields increase with applications of mineral N fertiliser (Andruszczak *et al.*, 2011; Koutroubas *et al.*, 2012), and benefit from non-synthetic compost applications as well (Caldwell *et al.*, 2014). In the FPT, five out of six conventional farm sites received at least one synthetic fertiliser, while only one out of seven organic sites with harvest-relevant data (Spindlestone excluded) received manure fertiliser (Table C.4., Appendix C). The impact of fertility applications on crop yield is further supported by significantly higher SPAD readings in spelt grown under conventional management, indicating increased plant nitrogen uptake during the growing season. The yield increase for conventional farms in the trial is also likely due to the use of synthetic crop protection methods, especially fungicides, which limits yield losses from disease. Synthetic herbicides and fungicides were applied on five out of six conventional sites included in the FPT, while organically managed sites used no crop protection inputs (Table C.5., Appendix C).

On farms that applied the experimental input biogas digestate, yields from digestate fertilisation were higher (2.69 t/ha) than from farm-based fertility (2.46 t/ha) but this difference was not significant. One of the farms within the biogas digestate trial was organic and did not apply any additional fertiliser while the remaining three conventional farms applied mineral N (Table C.4., Appendix C), which, like digestate, has high levels of plant-available nitrogen. SPAD readings throughout the growing period did not differ significantly at all but one assessment (GS47), when biogas digestate fertilised crops had significantly higher readings (44.3) than farm-based fertilised plants (39.2). The FPT results indicate that digestate can match and/or outperform mineral N as an alternative fertiliser across multiple farm environments.

Yield differences between varieties were not significant over the trial period, however Oberkulmer Rotkorn produced the highest yields when biogas digestate was not included as a fertiliser type (2.72 t/ha) while ZOR had the highest yields on farms that applied biogas digestate (2.74 t/ha). The lowest yielding varieties were Rubiota when digestate was not applied (2.49 t/ha) and Filderstolz on farms with biogas digestate (2.41 t/ha).

6.5.1.2 **PLANT HEIGHT**

Spelt plant height was higher in 2018 compared to 2017, both without biogas digestate (102.7cm compared to 109.6cm) and on the farms where digestate was included as a fertiliser input (98.3cm compared to 113.8cm). The taller crops in 2018 correspond with higher yields in this year. Plant height was significantly different between varieties whether or not biogas digestate was a fertiliser input, which was expected based on genetic differences. Oberkulmer Rotkorn (113.7 cm) and Rubiota (116.3 cm) are tall-growing varieties, while ZOR (99.8 cm) and Filderstolz (94.6 cm) are shorter genotypes. The taller varieties can outcompete weeds, but are at a higher risk of lodging (especially at higher rates of N fertiliser), which can negate potential yield increases. Lodging did occur in the FPT, particularly in the taller varieties, which likely affected any positive yield advantage for Oberkulmer Rotkorn and Rubiota.

6.5.1.3 **HARVEST INDEX**

The UK benchmark harvest index for winter wheat is 51%, indicating that the majority of crop mass is in the grain (AHDB, 2018b). Overall, the average HI for all spelt varieties in the FPT (without biogas digestate application) was 29.4%, which is much lower than expected for wheat but not unusual for spelt, which has a hull that contributes a larger portion of total biomass in the chaff once the grain is dehulled. The HI for spelt has been reported in the range of 29-41% in European studies (Winzeler *et al.*, 1993; Konvalina *et al.*, 2010; Koutroubas *et al.*, 2012; Konvalina *et al.*, 2014), and the spelt from the FPT falls at the low-end of that range. While harvest index is a benchmark for production efficiency, spelt is valued for producing taller straw for livestock bedding and as organic matter for soil fertiliser inputs, especially in stockless organic systems (Konvalina *et al.*, 2014).

Harvest index in the FPT did not differ significantly by management system, fertiliser type or variety. HI was higher in 2018 than 2017 without biogas digestate (32.8% and 26.0% respectively) and on farms that applied digestate (31.0% and 26.6% respectively). Between varieties, the shorter strawed genotypes, Filderstolz and ZOR, had slightly higher harvest indices (30.5% and 31.7% respectively) than the taller varieties, Oberkulmer Rotkorn (28.3%) and Rubiota (28.2%). Cereal-breeding techniques selecting for shorter-stemmed plants to improve harvest index have been implemented in spelt (Winzeler *et al.*, 1993; Longin and Würschum, 2014), and the higher HI in the varieties bred for shorter straw (Filderstolz and ZOR) reflects this breeding shift.

6.5.1.4 **LODGING SEVERITY**

Lodging severity was higher in 2018 than 2017, both without biogas digestate (2.71 and 1.00 respectively) and with biogas digesate (4.71 and 0.44 respectively) On farms that received biogas digestate fertiliser inputs, spelt grown under conventional management had significantly higher lodging severity (3.00) than organically managed spelt (0.44). This is likely due to higher N input, as conventional farmers applied higher nutrient-content and quantity fertiliser than organic farms (Table C.4., Appendix C). Lodging incidence in wheat grown in plot trials at Nafferton farm was significantly higher with mineral N applications compared to FYM composts (Rempelos *et al*., 2018), which supports the results of the FPT.

The taller varieties, Rubiota and Oberkulmer Rotkorn, had significantly higher lodging severity 3.29 and 2.93 respectively) than the shorter-stemmed ZOR (0.71) and Filderstolz (0.50), which is one of the caveats of taller-growing genotypes. Spelt landraces, like Oberkulmer Rotkorn, are associated with a higher risk of lodging due to their height (Keller *et al.*, 1999; Konvalina *et al.*, 2010; Koutroubas *et al.*, 2012; Longin and Würschum, 2014), but this sensitivity varies based on climatic conditions (Lacko-Bartošová *et al.*, 2010). In 2017, when lodging was not as severe, the taller landrace Oberkulmer produced the highest yields (2.34 t/ha), while in 2018, when lodging particularly affected taller genotypes, the shorter variety ZOR had the highest yield (3.15 t/ha). As noted previously, the climatic conditions in 2018 were much more unsettled, with a cold and snowy winter and very warm dry summer that gave way to late-season rainfall. In particular, the amount of rainfall in August was exceptionally high in 2018 (108.6mm) compared to 2017 (31.6mm) (Table A.3., Appendix A) and long-term averages for the region (57.2mm) (Table A.2., Appendix A). This increased precipitation after grain-fill contributed to lodging in susceptible varieties, which in turn likely contributed to low Hagberg Falling Number.

Lodging severity in the FPT was certainly impacted by genotype and climatic differences but considering lodging differences by site also highlights the impact of sowing date. In 2018, when lodging was much more prevalent, sites that experienced the most lodging were Moorhouse (5.50), Pawson (7.75) and Wheldon (4.25), which were all sown from three-weeks to a month earlier than other sites (Table 6.2.4). While delayed sowing negatively impacted rye establishment, it also reduced lodging in the taller spelt varieties. Two of these sites were still among the highest yielding (Moorhouse and Pawson), however grain quality (HFN and specific weight) was negatively impacted by lodging severity.

6.5.2 YIELD COMPONENTS

Higher spelt yield in the 2018 FPT is reflected in the yield components, with higher ears/m^2 (291), grains/m^2 (4969), grains/ear (17.8) and thousand grain weight (49.8g) in 2018 compared to 2017 (232 ears/m^2, 2803 grains/m^2, 12.5 grains/ear and 45.0g TGW). The yield components for spelt are much lower than typically found for wheat (460 ears/m^2 and 48 grains/ear (AHDB, 2018b)), which reflects overall lower yields for spelt compared to common wheats. Ears/ m^2 and grains/ m^2 were both significantly higher under conventional (293 and 4459 respectively) than organic management (238 and 3550 respectively), which corresponded with the higher yields on conventional farms. Biogas digestate applications did not have a major impact on yield components, except for grains/m^2, which were significantly higher when digestate was applied (4232) than farm-based fertiliser (3324).

TGW was significantly lower for the variety Rubiota (44.3g without digestate, 43.0g on farms with digestate) compared to all other varieties (46.3g to 49.4g), which was reflected in low final yields. TGW in the FPT is comparable to spelt grain weight from other field trials in Europe, which range from 43.5g to 57.7g (Lacko-Bartošová *et al.*, 2010; Andruszczak *et al.*, 2011; Pospišil *et al.*, 2011).

6.5.3 DISEASE SEVERITY

Yellow striped rust (*Puccinia striiformis*) was the most prevalent disease over both trial years, with higher disease severity levels in 2017 compared with 2018. Disease severity was significantly higher on the first two leaves under organic management (L1 AUDPC=108; L2 AUDPC=221) than conventional management (L1 AUDPC=39; L2 AUDPC=65). The difference between management systems is unsurprising, and likely contributed to lower organic yields, as the majority of conventional farms in the trial applied fungicides to control foliar disease, while organic farms did not (Table C.5., Appendix C). In a Croatian field trial, spelt yield was significantly higher when fungicide was applied in years when plants experienced high levels of powdery mildew and leaf rust (Pospišil *et al.*, 2011).

There was no significant difference in disease severity between fertiliser input types but differences in disease severity by variety were significant. The varieties ZOR and Filderstolz had the highest disease severity on the first three leaves (ZOR AUDPC L1=169, L2=250; Fild AUDPC L2=216, L3=617). These varieties were also the most affected by disease on the farms using biogas digestate fertiliser (ZOR AUDPC L1=162, L2=175; Fild AUDPC L2=168 L3=726). Filderstolz and ZOR are the more modern spelt varieties included in the FPT, bred for shorter-stems and higher yields. Oberkulmer Rotkorn, which had the lowest yellow rust disease severity, is noted for moderate disease resistance and had been used to develop yellow rust resistance in wheat x spelt crosses (Schmid *et al.*, 1994). This disease resistance likely contributed to Oberkulmer Rotkorn producing higher yields than other varieties, particularly in 2017, when disease levels were higher. Yellow rust severity did not appear to impact final yield results for ZOR, which was the highest yielding variety on farms including biogas digestate as a fertiliser input, however the lower yields of Filderstolz on these farms may be attributed in part to its disease susceptibility.

Powdery mildew (*Blumeria graminis*) was present in spelt during the growing season, but in much lower quantities than yellow rust. On the bottom two leaves, mildew severity was higher in 2017 (L3 AUDPC=22, L4 AUDPC=51) compared to 2018 (L3 AUDPC=1, L4 AUDPC=3). Rubiota had significantly higher disease severity on Leaf 2 than all other varieties (AUDPC=13) and on farms with biogas digestate applications, digestate had significantly higher disease levels than farm-based fertility on Leaf 4 (AUDPC=9), otherwise management, fertiliser type and variety did not have a significant effect on powdery mildew presence in spelt.

Signs of ergot (*Claviceps purpurea*) were present on spelt ears in both trial years, but there were no significant main or interaction effects for management, fertiliser type or variety. Percent disease cover on spelt ears was slightly higher in 2017 (2.25%) compared to 2018 (0.89%), however any ergot indications pre-harvest were noted outside of the grain hull, which was removed during processing and likely did not affect final grain quality.

6.5.4 GRAIN MILLING QUALITY

In 2017, UK winter wheat quality for high-quality bread-making was typical, but poor compared to 2016, which was an exceptional year for milling-wheat quality (AHDB, 2017). The 2018 UK wheat grain had improved quality overall, but slightly lower protein content than 2017 (AHDB, 2018a). Over the two-years of the FPT, specific weight and HFN were higher in 2018 compared to 2017, while protein was higher in 2017 (Table 3.4.2).

Table 6.5.1. Grain quality for hard-wheat grown in the UK in 2017 and 2018, including country-wide averages and regional averages for the North.

	2017		**2018**	
	UK	**North**	**UK**	**North**
Specific weight (kg/hl)	76.0	76.8	77.9	78.2
Protein (%)	13.2	12.5	12.7	11.9
Hagberg Falling Number (s)	260	283	327	318

Data from Agriculture and Horticulture Development Board (AHDB) Cereal Quality Surveys (AHDB, 2017; AHDB, 2018a).

6.5.4.1 SPECIFIC WEIGHT

The UK milling wheat averages for specific weight were 76.0 kg/hl in 2017 and 77.9 kg/hl in 2018 (Table 3.4.2). The spelt in the FPT met the minimum threshold for hard wheat (76 kg/hl) in both 2017 (78.7 kg/hl) and 2018 (77.4 kg/hl). Regionally, specific weight averages in the North were higher than the national average in both years (76.8 kg/hl in 2017; 78.2 kg/hl in 2018) and the spelt trial results were above the Northern average in 2017 but below it in 2018.

Specific weight of spelt grown under conventional management (77.5 kg/hl) was significantly lower than specific weight of organically managed spelt (78.5 kg/hl), but both management systems produced spelt that met the minimum UK requirement. Rubiota and ZOR had significantly higher specific weights (78.0 and 79.1 kg/hl respectively) than Filderstolz and Oberkulmer Rotkorn (77.7 and 77.2 kg/hl respectively) and on farms applying biogas digestate, ZOR specific weight was significantly higher (79.5 kg/hl) than all other varieties. Regardless of fertility applications, all varieties met the minimum hard-wheat specification for specific weight.

6.5.4.2 PROTEIN CONTENT

The UK hard milling wheat averages for protein were 13.2% in 2017 and 12.7% in 2018 (Table 3.4.2). The spelt in the FPT was above the minimum requirement (13%) and national averages for wheat in both 2017 (14.3%) and 2018 (14.0%). The FPT produced spelt with higher protein than wheats grown in the UK in the same year, which reflects previous research finding that spelt has higher grain protein content than modern wheat (Abdel-Aal *et al.*, 1995; Codianni *et al.*, 1996; Ranhotra *et al.*, 1996b; Abdel-Aal *et al.*, 1997; Bonafaccia *et al.*, 2000; Gomez-Becerra *et al.*, 2010; Stolickova and Konvalina, 2014; Longin *et al.*, 2015; Bernas *et al.*, 2016).

Spelt protein content was significantly higher under conventional management (14.7%) than organic management (13.6%), which was also the case on farms where biogas digestate was used as a fertiliser input (15.4% conventional, 13.0% organic). The difference in protein between management systems is likely due to higher nitrogen availability in conventional management systems, as grain protein content is calculated directly from grain N content (Merrill and Watt, 1955).

The taller spelt varieties, Oberkulmer Rotkorn and Rubiota, had the highest protein content (14.9% and 14.8% respectively) while the semi-dwarf genotype Filderstolz (13.3%) had significantly lower protein content compared to other varieties except ZOR (13.5%). On farms that included biogas digestate applications, Oberkulmer Rotkorn and Rubiota had significantly higher protein content (both 15.9%) than Filderstolz and ZOR (both 13.6%). All varieties met the minimum protein content specification for hard-wheats.

6.5.4.3 HAGBERG FALLING NUMBER

The UK milling wheat averages for Hagberg Falling Number were 260 seconds in 2017 and 327 seconds in 2018 (Table 3.4.2). Spelt from the FPT exceeded the minimum specification (250 seconds) and national average in 2017 (321 seconds) but fell below the standard in 2018 (167 seconds). As discussed previously, lodging was a detrimental presence in 2018 and had an impact on HFN in particular, as lodged plants left spelt grains susceptible to ground-level damp, which can cause early grain sprouting.

There were no significant differences in HFN between management, fertiliser type or variety. On farms where biogas digestate was a fertiliser input, none of the varieties met the minimum falling number specification for hard-milling wheats. When biogas digestate was not included, the varieties Filderstolz and Rubiota met the minimum requirement for HFN (256 and 262 seconds respectively), while Oberkulmer Rotkorn (216 seconds) and ZOR (219 seconds) did not. In 2017, all of the varieties met the minimum falling number specification, ranging from 360 seconds for Rubiota and 298 seconds in ZOR, while in 2018, lodging contributed to low HFNs that did not meet minimum specification, ranging from 199 seconds in Filderstolz to 142 seconds in Oberkulmer Rotkorn.

The climate differences between years affected overall HFN quality and had different impacts based on individual site. The lowest Falling Number in 2017 was recorded at Spindlestone (156 seconds), which was the result of exceptionally late harvest (Table 6.2.4) and grain quality data from this site was not included in analyses for this reason. In 2018, lodging affected HFN, which is particularly reflected at Moorhouse and Pawson, which had the lowest falling numbers (75 and 80 seconds respectively) and highest lodging severity (5.50 and 7.75 respectively). As discussed previously, higher lodging in 2018 at these sites is the combined result of earlier sowing, higher fertiliser inputs and heavy precipitation pre-harvest. The high August rainfall in 2018 (Table A.3., Appendix A) likely also contributed to overall lower HFN in the FPT in that year, as wet weather conditions during grain maturation negatively influence Falling Number in spelt (Lacko-Bartošová *et al.*, 2010).

6.6 RYE DISCUSSION

Poor establishment contributed to a smaller and unbalanced dataset available to evaluate rye performance. Instead, means and standard errors were presented in the results and will be discussed in this section.

6.6.1 GRAIN HARVEST

6.6.1.1 GRAIN YIELD

Rye grain yield in the trial was higher in 2018 compared to 2017, which goes against yield differences for cereals in the UK between the two years, although minor grain cereals produced higher yields in 2018 (DEFRA, 2018a). DEFRA does not maintain annual rye yields on a national scale in the UK, but rye is grouped in with mixed corn and triticale and reported as minor cereals. Minor cereal yields increased from 2.3 t/ha to 3.8 t/ha from 2017 to 2018 (DEFRA, 2018a) and rye and triticale (rye x wheat cross) are known for drought tolerance (Tupits, 2008; Schlegel, 2014), which was an advantage in most of the UK during the dry summer of 2018. In the FPT, rye grain yield was 45% higher in 2018 (4.09 t/ha) compared to 2017 (2.24 t/ha).

The rye trials were established well-enough to complete assessments on ten sites. In 2017, none of the rye varieties established at Moorhouse or Wheldon and only one variety grew at Newlands; in 2018, rye did not establish at all at Gilchesters 2 or Three-Corners field and only two varieties grew at Applebys Whin and three at Tughall (Table 6.3.4). In 2017, poor rye establishment was likely due to late sowing and high slug damage, while in 2018 establishment was impacted by sowing date and seed source. Sowing was a month later in 2018 compared with 2017, and even though rye did grow successfully at five sites, yields were much lower in 2017. Rye establishes well when daily temperatures range between 10-15 °C (Nuttonson, 1958), and though delayed sowing is possible, this varies by climatic conditions and can result in substantial yield losses (McDonald, 1991; Budzyński *et al.*, 2003). Poor establishment in 2018 occurred on sites that were sown three-weeks to a month after the ideal sowing time in late September. Additionally, limited seed supply from the HMC project meant that these sites also used farm-saved seed grown on a participatory farm in 2017. While the seed was stored and cleaned prior to sowing, it may have been of lower quality and therefore germination potential than certified seed. Although spelt was also sown from the 2017 FPT, the protective hull of the grain likely prevented deterioration prior to sowing and seems to provide much greater tolerance to slug predation than is the case for rye.

Rye yield was highest in 2017 in the single variety at Newlands (3.27 t/ha), followed by Gibside (2.44 t/ha) and Quarry fields (2.27 t/ha) while Spindlestone produced the lowest yields by far (0.45 t/ha). In 2018, the highest rye yields occurred at Moorhouse (5.67 t/ha) and Pawson (4.37 t/ha), while the lowest occurred at Applebys Whin (0.46 t/ha). As was discussed for spelt, yield data from Spindlestone, which was harvested exceptionally late, contributing to yield losses, was not included in yield and harvest-related means tables, excepting in considering differences between sites. Applebys Whin also had exceptionally low yields, which, as noted, is likely due to poor establishment after late sowing with farm-saved seed.

Cereal yield differences in 2018 in the UK are attributed to weather variability, as a cold spring with high rainfall and a long, dry summer with high temperatures resulted in yields varying throughout the country (DEFRA, 2018a). Radiation likely contributed to higher yields in 2018, as rye benefits from sunny, warm weather with moderate moisture during the growing season (Kunkulberga *et al.*, 2017) and cold, rainy conditions during flowering creates spikes with empty florets (Bushuk, 1976). As noted for spelt, Northeast England had more sunshine hours in 2018 than 2017 (MetOffice, 2018b) and data from Nafferton farm showed that total radiation was higher in 2018, including over May, June and July (Table A.3., Appendix A).

Conventional management systems had higher yields (3.69 t/ha) than organic systems (2.23 t/ha) likely due to crop protection measures and higher N applications from fertiliser inputs under conventional management. European field trials show that rye yields increase with fertiliser applications (Nedzinskienė, 2006; Gollner *et al.*, 2011; Schlegel, 2014; Stepień *et al.*, 2016). Three out of four conventional farm sites where rye was evaluated received at least one synthetic fertiliser, while only one out of five organic sites (Spindlestone excluded) received manure fertiliser (Table C.4., Appendix C). Biogas digestate also produced higher yields (3.70 t/ha) than farm-based fertility (2.80 t/ha), although as noted, two of the farms applying digestate did not include a farm-based fertiliser input (Table C.4., Appendix C), which might have minimised the yield differences between fertiliser types. Higher yields under conventional management and with biogas digestate applications due to higher N inputs is also reflected in SPAD readings, which were higher for conventional management and biogas digestate fertiliser at all four assessment growth stages. The FPT results for rye, as with spelt, demonstrate the potential for digestate to match and/or outperform mineral N as an alternative fertiliser.

The modern Austrian variety Elias was the highest yielding (3.76 t/ha), with the modern Polish genotype Dankowksie Amber not far behind (3.69 t/ha). The old Austrian variety Schlaegler had the lowest yields (2.43 t/ha), while the modern Estonian Elvi was slightly higher (2.78 t/ha).

6.6.1.2 **PLANT HEIGHT**

Rye plant height was higher in 2018 (154cm) compared to 2017 (133cm), but the main observable differences in plant height occurred between varieties. The old Austrian genotype, Schlaegler was the tallest (155cm), while the modern Polish variety Dankowskie Amber was the shortest (132cm) and the modern Estonian Elvi and Austrian Elias had intermediate heights (both 142cm). Taller plants did not translate to higher yields in rye, which reflect the small differences in height between varieties.

6.6.1.3 **HARVEST INDEX**

Due to much higher straw production from taller plants, rye HI is expected to be much lower than that of wheat. Over the two-year trial, the average harvest index for all rye varieties was 42.6%, with higher HI in 2018 (44.4%) compared to 2017 (40.7%). The older variety Schlaegler had a lower HI (37.1%) than the other modern varieties (44.0-44.7%). As the tallest genotype, Schlaegler produced more straw than the other varieties, which contributed to a lower grain yield to plant biomass ratio.

6.6.1.4 LODGING SEVERITY

Lodging severity in rye was higher in 2018 (4.00) than 2017 (0.66) and under conventional (3.22) compared to organic management (0.73). The differences in lodging between management systems is likely due to fertiliser inputs, as conventional farmers applied higher levels of nutrients than organic farms (Table C.4., Appendix C) and as noted, the relationship between higher lodging incidence with mineral N fertility compared to composted FYM has previously been observed in wheat grown in Nafferton farm field trials (Rempelos *et al.*, 2018).

The tallest variety, Schlaegler, had the highest lodging severity (4.50) of all varieties, while the shortest variety, Dankowskie Amber, had the lowest lodging severity (0.31). Due to its height, rye is considered a lodging risk, although the amount of precipitation during the growing season has a greater influence on rye lodging than plant height (Peltonen-Sainio *et al.*, 2002; Peltonen-Sainio *et al.*, 2010b). While plants were taller overall in the second trial year and lodging was also higher in this year, climatic differences, especially precipitation, likely impacted lodging severity in 2018. As discussed, August rainfall was exceptionally high in 2018 (108.6mm) (Table A.4., Appendix A), which likely contributed to increased lodging and yield losses, particularly in the variety Schlaegler, which was the lowest yielding variety in 2018 (2.89 t/ha).

Lodging differences by site were likely impacted by sowing date. The sites that experienced the most lodging in 2018, when high August rainfall contributed to higher lodging risk, were Pawson (5.75) and Moorhouse (4.75), which were sown from three-weeks to a month earlier than all other sites except Wheldon. Wheldon was organically managed, which indicates that higher lodging severity was the combination of high precipitation, increased fertiliser inputs and late sowing date.

6.6.2 YIELD COMPONENTS

The higher grain yield in 2018 is reflected in higher ears/m^2 (317), grains/m^2 (15350), grains/ear (47.8) and thousand grain weight (37.3g) compared to 2017 (222 ears/m^2, 8714 grains/m^2, 42 grains/ear and 36.6g TGW).

Ears/ m^2 and grains/m^2 were both much higher under conventional (301 and 13672 respectively) than organic management (214 and 9117 respectively), which was reflected in higher yields on conventional farms. This was also true for biogas digestate fertiliser treatments, although the differences were not as large. Ears/m^2 with digestate (337) were higher than with farm-based fertility (224) and grains/m^2 were also higher for digestate (14576) than without (10336). Grains/ear and TGW did not differ substantially between management systems and fertiliser types, but in terms of variety, Schlaegler had the lowest grains/ear (39.6) and TGW (32.8g), reflected in the lowest yields of all varieties.

6.6.3 DISEASE SEVERITY

Brown leaf rust (*Puccinia recondita*) was the most prevalent disease in the FPT rye over both trial years, with higher disease severity levels in 2018 compared with 2017. Disease severity was higher on the first two leaves under organic management (L1 AUDPC=164; 2 AUDPC=312) than conventional management (L1 AUDPC=88; L2 AUDPC=145). The difference between management systems is unsurprising, and likely contributed to lower organic yields, as effective fungicides are available to control brown leaf rust in rye (Schlegel, 2014). The majority of conventional farms in the trial applied fungicides to control foliar disease, while organic farms did not (Table C.5., Appendix C). On L3 and L4, brown rust disease severity was higher under conventional (L3 AUDPC=298; L4 AUDPC=279) compared to organic management (L3 AUDPC=238; L4 AUDPC=117), which may reflect the lower efficiency of the fungicide treatments in controlling disease on the lower leaves.

Farm-based fertility had higher brown rust disease severity on the top two leaves (L1 AUDPC=145; L2 AUDPC=258) compared to biogas digestate (L1 AUDPC=75; L2 AUDPC=135), however this was reversed for the bottom two leaves as biogas digesate fertilised plants had higher disease levels (L3 AUDPC=287; L4 AUDPC=282) than farm-based fertilised plants (L3 AUDPC=266; L4 AUDPC=172). This pattern is likely reflective of the differences between organic and conventional management because out of the five farms with rye that applied biogas digestate, three applied fungicides, which likely reduced disease levels on upper plant leaves.

The variety Elvi had the highest brown rust disease severity on all four leaves (L1 AUDPC=246; L2 AUDPC=347; L3 AUDPC=428; L4 AUDPC=420), and Schlaegler also had high disease levels (L1 AUDPC=130; L2 AUDPC=311; L3 AUDPC=399; L4 AUDPC=249), which may have contributed to lower grain yields for both varieties.

Leaf disease is not considered a major problem for rye production, however ear disease can contribute to yield and quality losses. Ergot (*Claviceps purpurea*) was present on rye ears in both trial years, with higher percent disease cover in 2017 (3.02%) than 2018 (2.24%). Rye is more sensitive to ergot infection than other cereals, especially if conditions are wet after flowering and plants are sparsely planted (Bushuk, 1976; Schlegel, 2014). In both trial years, rye completed flowering in mid-June, which had much higher monthly total rainfall in 2017

(127.2mm) compared to 2018 (33.8mm) (Table A.3, Appendix A). Although ergot levels were low overall, the variation in precipitation likely contributed to differences in ergot presence in rye between years.

6.6.4 GRAIN MILLING QUALITY

6.6.4.1 SPECIFIC WEIGHT

The rye in the FPT did not meet the minimum specific weight threshold (72 kg/hl) in either year. Specific weight was higher in 2018 (70.2 kg/hl) than 2017 (68.5 kg/hl). Warm, sunny weather leads to higher specific weight (Hansen *et al.*, 2004) and rainy summer conditions contribute to low specific weights (Salmenkallio-Marttila and Hovinen, 2005). The summer months of 2018 were notably warm, sunny and dry (DEFRA, 2018a), which likely influenced specific weight, although the lower test weights overall indicate that climate conditions in both years were not ideal for rye grain development. Schlaegler had a particularly low specific weight (66.9 kg/hl) compared to other varieties.

6.6.4.2 PROTEIN CONTENT

The FPT rye met the minimum protein requirement (7-11%) in both trial years. Protein content was very similar between years and fertiliser types but was higher under conventional (11.9%) than organic management (10.4%). The protein difference between management systems is likely due to higher N inputs from conventional fertilisation, as mineral fertilisers have been shown to increase protein content in rye grain (Stepień *et al.*, 2016; Mishra *et al.*, 2017). Elias had the lowest protein content (10.7%) and Schlaegler had the highest protein (12.2%) but all four varieties met the minimum UK standard.

As discussed in Chapter 4, rye is recognised as having much lower protein content than wheat (Nuttonson, 1958; McDonald, 1991; Kowieska *et al.*, 2011). Bakers who work regularly with rye do not rely on typical quality metrics that were designated along with the Chorleywood Bread Process, which rely on high-energy minerals and chemicals for quick-rise bread, but do not apply to slow-fermentation methods (Whitley, 2009). The protein results from the FPT fall well within the range of what millers and bakers typically expect from bread-making rye varieties.

6.6.4.3 HAGBERG FALLING NUMBER

The rye in the FPT met the minimum HFN specification (110 seconds) in 2017 (127 seconds) but not in 2018 (81 seconds). The difference in HFN between years was likely affected by lodging in 2018, although lodging was less severe for rye than spelt, so other factors were certainly at play. Low Falling Number has been the main quality limitation to increasing rye production in the UK (McDonald, 1991) and rye is susceptible to sprouting in the ear due to low harvest dormancy, which results from high alpha-amylase activity and low HFN (Schlegel, 2014).

Falling number did not differ substantially by management system or fertiliser type, but among varieties Dankowskie Amber had the highest HFN (121 seconds) and Elias also met the minimum UK specification (118 seconds), while Schlaegler and Elvi were lower than the typically accepted HFN (90 and 87 seconds respectively). In 2017, all of the varieties met the minimum falling number specification except Elvi (102 seconds), as Elias (146 seconds) and Dankowskie Amber (143 seconds) had the highest HFN, while in 2018, lodging contributed to low HFNs that did not meet minimum specification, ranging from 39 seconds in Schlaegler to 93 seconds in Elias.

As was the case in spelt, yearly climate differences affected HFN, both directly and as an influence of lodging severity. The lowest HFN in 2017 was at Spindlestone (64 seconds), due to an exceptionally late harvest (Table 6.2.4) and as discussed, grain quality data from the site was not included in relevant means tables. In 2018, only one FPT site, Wheldon, produced rye that met the minimum HFN specification (112 seconds). The two sites with the lowest HFN, Moorhouse (71 seconds) and Pawson (72 seconds), also experienced the highest lodging severity (4.75 and 5.75 respectively), which, as discussed, is the result of early sowing, higher fertiliser inputs and heavy precipitation pre-harvest. Similar to other cereals, wet conditions pre-harvest reduce rye HFN (McDonald, 1991; Hansen *et al.*, 2004; Salmenkallio-Marttila and Hovinen, 2005; Tupits, 2008; Kunkulberga *et al.*, 2017), and the high rainfall in August 2018 (Table A.3., Appendix A) likely contributed to overall lower Falling Number in rye in 2018 compared to 2017.

6.7 **CONCLUSIONS**

The two-year Farmer Participatory trial demonstrates the value of on-farm trials to identify viable genotypes and agronomic practices but also reveals the challenges of conducting a multi-site trial. Although low replication and poor establishment prevented vigorous statistical analyses, especially in rye, the results from the FPT provide farm-based context for the results of the factorial spelt and rye trials at Nafferton farm.

Following the Nafferton-farm trial, spelt grown in the FPT further supports the development of milling-quality spelt in North East England. Yield variation between years was not unusual and although lodging contributed some yield loss and reduced grain quality in taller varieties in 2018, spelt in both years met bread-making milling quality standards. The overall yield advantage under conventional management supports the use of low-level fertiliser inputs, including in organic systems, to improve final spelt yields. Oberkulmer Rotkorn, which was the most promising variety in the Nafferton trial, also performed well in the FPT, and ZOR, a shorter-stemmed genotype, yielded well under higher fertiliser inputs. Although lower HFN in both varieties reflects some quality susceptibility, the trial demonstrates the potential of high-quality bread-making spelt to be grown in varied locations and climates in the UK. A key issue to keep in mind is the very low yields compared to wheat, which means that spelt would need to trade at a much higher premium to make the crop economically viable for farmers.

The rye component of the FPT does not as clearly support the results of the Nafferton farm trial, as it exposed a great deal of inconsistency and variability in successfully growing bread-quality rye. Elias was the highest yielding variety in both the Nafferton trial and the FPT, however poor establishment and low HFN across multiple sites reflect major risks for growers considering rye as an alternative grain. Sowing and harvesting at optimal dates for warm, dry weather are essential for rye yield and quality, because without establishment, fertiliser input and management advantages are inconsequential.

Biogas digestate as an alternative fertiliser is supported by increased yields in the FPT, however the limitations for its commercial use were also on display. Replications of digestate applications were limited by accessibility and derogation requirements on organic farms. Applying digestate is only available to farms within reasonable distance to an anaerobic digestion plant and requires additional cost for transport and contracted application, but this could still mean a significant cost saving when compared with mineral fertiliser.

Although the Farmer Participatory trial was not without faults, the results reflect the potential of both minor cereal crop development in the North East UK and on-farm trials to evaluate alternative agronomic practices across varied conditions.

CHAPTER 7. GENERAL DISCUSSION

7.1 INTRODUCTION

The overall aim of the spelt and rye trials was to consider the viability of growing bread-making quality spelt and rye by evaluating contrasting varieties and different fertiliser inputs on farms in North East England. Results from each of the two-year trials were evaluated separately in previous chapters but here they are considered together to suggest future recommendations for research and agricultural practice.

The aims were to identify any consistencies between both crop species, including how both spelt and rye respond to biogas digestate applications compared to mineral N and organic composted FYM and whether older varieties/landraces have yield/quality advantages over modern varieties. The outcomes from the Farmer Participatory trial provide an opportunity to evaluate genotype x environment responses and differences in spelt and rye performance in organic and non-organic systems.

Beyond trial results, the economic viability of growing spelt and/or rye in the North East is an additional consideration for any recommendations derived from this research. Any novel crop is only valuable to a producer if it is profitable or provides additional benefits to a whole crop rotation, and while spelt and rye milling quality varieties have strong market potential, the reality of production costs and commodity prices provide a clearer picture.

Finally, future research topics are included, both as a continuation of the evaluations from the trials and as improvements for additional work. Especially with regard to the Farmer Participatory trial, the value of the farmer network and online database established for the trial will only be fully realised with continued use and development. Even as spelt and rye are growing in use by farmers, millers and bakers in the UK, continued development of these minor cereals requires further collaborative work between researchers, growers and processors/end-users.

7.2 BIOGAS DIGESTATE

Both organic and conventional fertility applications have been shown to increase grain yield in spelt (Andruszczak *et al.*, 2011; Koutroubas *et al.*, 2012; Caldwell *et al.*, 2014) and rye (Nedzinskienė, 2006; Gollner *et al.*, 2011; Schlegel, 2014; Stepień *et al.*, 2016). In the Nafferton farm field trials, fertiliser type had a significant main effect on grain yield in both crops. In spelt, biogas digestate produced significantly higher yields (3.64 t/ha) than all other fertiliser types, including mineral N (3.08 t/ha), while for rye, yields for biogas digestate (5.13 t/ha) and mineral N (5.21 t/ha) were similar and significantly higher than the manure-based fertilisers (cattle slurry and composted FYM). SPAD readings from the field trials also demonstrate the potential of biogas digestate as a readily available source of N, particularly for organic but also for conventional production systems.

The results of the Nafferton field trial support the use of biogas digestate as an alternative fertiliser, both as a comparable mineral N replacement in conventional production systems and as a higher-yielding substitute for manure-based fertility under organic management. Anaerobic Digestion is valued as a renewable energy source that sustainably recycles waste materials while reducing greenhouse gas emissions and storing carbon (Tambone *et al.*, 2010). While specific nutrient-content varies in digestate based on feed-stock, process operating conditions, etc., biogas digestate provides more plant readily available nitrogen than other non-synthetic fertilisers (Tambone *et al.*, 2010; Alburquerque *et al.*, 2012; Möller and Müller, 2012; Wentzel *et al.*, 2015) and the benefit of spring-time applications were apparent in the field trials for both spelt and rye.

While digestate out-performed other fertilisers in the field trial, its availability to farmers can be limited, based on the proximity of the nearest AD plant and derogation requirements for organic production. This proved the case in the Farmer Participatory trial, as only four out of seven farms in 2017 and three out of seven in 2018 were able to apply digestate, although the number of AD facilities is on the rise, with more than 400 systems currently in the UK (NNFCC, 2018). The nutrient availability in digestate is also dependent on original feedstock total N content, as higher N content results in higher ammonium in digestate but high ammonium can inhibit microbial activity and biogas production, leading to system inefficiencies (Möller and Müller, 2012). In the case of the spelt and rye trials, the primary AD feedstock was grass silage, which had a dry matter N content of 10% in 2015 and 6.23% in 2016. This difference between years shows the variability in nutrient content that can exist in biogas digestate when using the same feedstock, which only increases when different feedstocks are considered. That said, the yield benefit of digestate applications occurred for both spelt and rye throughout the field trial, demonstrating the benefit of digestate as an alternative fertiliser.

7.3 **VARIETY CHOICE**

The genotypes included in the Nafferton farm field trial included both modern varieties and older varieties/landraces. The more recent spelt varieties included the shorter-stemmed Swiss

ZOR, the German spelt x wheat cross Filderstolz and the modern Czech variety Rubiota. The modern rye genotypes included the Estonian-bred Elvi, Austrian Elias and Polish-bred Dankowskie Amber. The two older varieties included a spelt Swiss landrace, Oberkulmer Rotkorn, and the Austrian rye Schlaegler. Cultivars that have not adapted to local climate conditions are outperformed by adapted cultivars, especially in years with non-ideal weather conditions (Hansen *et al.*, 2004). None of the varieties in the trial were bred or are typically grown in the UK, thus the results of the field trial provide insight into which genotypes have potential in the climate of North East England.

In spelt, the old Swiss landrace, Oberkulmer Rotkorn, produced the highest yield of the Nafferton farm field trial (3.74 t/ha), while the modern semi-dwarf German cultivar Filderstolz had the lowest yield (2.60 t/ha). In rye, the modern Austrian variety Elias produced the highest yield (5.59 t/ha) in the field trial and the older Austrian variety Schlaegler and modern Estonian Elvi had the lowest yields (4.01 and 4.22 t/ha respectively). Based on yield performance, the modern and older varieties were not consistent across both crop species, as a landrace was the highest yielding genotype in spelt but one of the lowest yielding in rye. The main advantage of the spelt landrace, Oberkulmer Rotkorn, was an ability to withstand high levels of yellow rust incidence compared with more susceptible modern varieties. The recent evolution of different races of yellow rust in Europe (Hovmøller *et al.*, 2016) has increased pressure on breeders to develop more robust resistance mechanisms than the single gene resistance typical in many modern cereal varieties (Schwessinger, 2017).

Older landraces are valued for disease and pest resistance (Newton *et al.*, 2010) and the spelt landrace Oberkulmer Rotkorn has been used to develop yellow rust resistance in wheat x spelt hybrids (Schmid *et al.*, 1994). In the field trials, the lowest yielding variety, Filderstolz, was also the most severely impacted by yellow rust leaf disease, as breeding for higher-yield and harvest index through wheat genetics seem to have diminished disease resistance in this genotype. With high yellow rust disease pressure in the field trials, the older variety had the performance advantage over the more modern variety. The Nafferton field trial did not include fungicide applications in either trial year, which might have reduced disease pressure on Filderstolz and decreased the yield advantage for Oberklumer Rotkorn. Variety response to fungicide treatments, though not observed in the field trials, is an area for future research.

Disease presence in rye was much lower than spelt, and rye as a species is considered less susceptible to foliar fungal pathogens than the major cereals, especially wheat and barley (Nuttonson, 1958; Bushuk, 1976; McDonald, 1991; Schlegel, 2014). One of the lower-yielding varieties, Elvi, experienced higher levels of powdery mildew than all other varieties, which may reflect a similar lack of disease resistance in a modern variety as demonstrated in spelt, however the main limitation to rye yield was poor establishment. Rye germination was exceptionally low for Elvi in 2015 (22%) and Schlaegler in 2016 (32%), reflecting lowest yields for Elvi in 2015 (4.7 t/ha) and for Schlaegler in 2016 (3.1 t/ha). Even with fungicides reducing disease pressure, it is unlikely that Elvi and Schlaegler would have substantial yield gains as these varieties seem ill-suited to establishing well in the North East UK climate.

Based on yield performance, an old spelt landrace and a modern rye cultivar were the preferred varieties from the Nafferton field trials. When grain milling quality specifications are factored in, the same rye genotype, Elias, was the most consistent across all parameters while the spelt genotype, Oberkulmer Rotkorn, was not the highest performing spelt variety. Although Oberkulmer Rotkorn grain had a high protein content (14.8%), the Swiss variety did not meet minimum hard-wheat milling specifications (NABIM, 2018) for specific weight (74.2 kg/hl) or Hagberg Falling Number (230 seconds). Instead, the modern Czech variety, Rubiota, had the highest specific weight (76.2 kg/hl), protein content (14.8%) and HFN (259 seconds) among all spelt varieties in the field trials. In rye, Elias had the highest specific weight (71.3 kg/hl) and HFN (126.6 seconds) among all varieties in the field trials. Although Elias had the lowest protein content (8.8%), most of the rye genotypes did not meet the minimum typical parameter requirements for milling especially for specific weight (minimum 72 kg/hl) and HFN (minimum 110 seconds) (A. Wilkinson, pers. comm.).

Rye is known to have much lower protein content than wheat (Nuttonson, 1958; McDonald, 1991; Kowieska *et al.*, 2011) and is susceptible to low falling numbers (Bushuk, 1976; McDonald, 1991). Because of this, bakers who work with rye flours are not reliant on typical quality metrics for hard-wheats and are prepared to utilise alternative methods to produce rye-based products, including sourdoughs and mixed-flour breads (Schlegel, 2014). The same artisan baking approach can also be applied to spelt, especially when considering that milling wheat quality specifications are based on the requirements of the Chorleywood Process for industrial bread-making (Cauvain and Young, 2006), which are reliant on high-energy minerals and chemicals for quick rise white bread, unlike slow-fermentation bread-making, which is much more forgiving in terms of protein and HFN (Whitley, 2009). With this in mind, the lower grain quality results of Oberkulmer Rotkorn are not unexpected for an old landrace and bakers inclined to work with spelt are familiar with sourdough and other non-industrial processes that are not reliant on typical quality metrics.

Considering both grain yield and grain quality parameters included in the Nafferton field trial, neither the old landraces nor modern genotypes were definitively top-performers for both crop species. That said, the landrace Oberkulmer Rotkorn was the top spelt variety and would be particularly recommended for organic systems, due to its disease resistance while the modern variety Elias was the highest performing rye variety. While other spelt varieties included in the trial may also be viable depending on final-end use (e.g. Rubiota had high quality parameters) or management system (e.g. Filderstolz and ZOR may yield more when fungicides are applied), the poor performance of Elvi and Schlaegler indicated that they are both ill-adapted to the conditions in North East England.

7.4 FARMER PARTICIPATORY TRIAL

The results of the Nafferton farm field trial (NFT) were further explored across multiple sites in the Farmer Participatory trial (FPT), as biogas digestate and spelt/rye cultivars were evaluated on organic and conventionally managed farms. Considering that both spelt and rye are considered well-suited to low-input and organic agriculture, this also provided an opportunity to consider management system as a factor in crop yield and quality.

7.4.1 BIOGAS DIGESTATE

In the NFT, both spelt and rye yields were significantly higher with biogas digestate applications (spelt: 3.64 t/ha; rye: 5.13 t/ha) than other organic fertilisers. In the FPT, yields for both crops were higher with digestate (spelt: 2.69 t/ha; rye: 3.70 t/ha) compared to farm-based fertility (spelt: 2.46 t/ha; rye: 2.80 t/ha), though neither difference was statistically significant. Digestate was not available as an alternative fertiliser input at all sites due to transport costs and Organic Derogation requirements, which limited the robustness of this analysis. Despite this limitation, yields from digestate applications supported the results of the Nafferton field trial, especially considering that the majority of farms that applied digestate applied mineral N as the farm-based fertiliser treatment. As was demonstrated by yields and SPAD readings in both spelt and rye in the NFT, the high quantity of readily available nitrogen provided by biogas digestate means that its efficiency of utilisation is similar to mineral N and the FPT demonstrates that digestate can match or exceed mineral N yields on non-organic farms. Although only one organic farm applied biogas digestate, the Farmer Participatory trial results also demonstrate the value of digestate in organic systems, as spelt yields on this farm were higher with digestate (1.45 t/ha), than without (1.29 t/ha), and much higher for rye with digestate (2.62 t/ha) than without (1.13 t/ha).

7.4.2 VARIETY CHOICE

Oberkulmer Rotkorn and Elias were the stand-out varieties from the Nafferton field trial for spelt and rye respectively and these varieties were also the highest yielding in the Farmer Participatory trial. Oberkulmer Rotkorn yielded 3.74 t/ha and 2.72 t/ha while Elias yielded 5.59 t/ha and 3.76 t/ha in the NFT and FPT respectively (Table 3.3.3). The same rye varieties with the lowest yields at Nafferton (Elvi: 4.22 t/ha; Schlaegler: 4.01 t/ha) also produced the lowest yields on farms (Elvi: 2.78 t/ha; Schlaegler: 2.43 t/ha) (Table 3.3.3), while the lowest yielding spelt variety was different between trials. In the NFT, Filderstolz was the lowest yielding (2.60 t/ha), likely due to high yellow rust susceptibility, but Rubiota had the lowest yield in the FPT (2.49 t/ha) as this variety was the most affected by lodging (Table 3.3.3).

Table 7.4.1. Spelt and rye grain yield and lodging severity means by variety from the Nafferton field trial (NFT) and Farmer Participatory trial (FPT).

	Grain Yield (t/ha)		**Lodging Severity**$^{+}$	
Spelt	**NFT**	**FPT**	**NFT**	**FPT**
Filderstolz	2.60	2.60	0	0.50
Oberkulmer Rotkorn	3.74	2.72	0	2.93
Rubiota	3.32	2.49	0	3.29
ZOR	3.26	2.69	0	0.71
Rye				
Dankowskie Amber	5.13	3.69	0	0.31
Elias	5.59	3.76	0	2.71
Elvi	4.22	2.78	0	1.08
Schlaegler	4.01	2.43	0	4.50

$^{+}$Lodging severity is measured on a 0-9 scale (0=upright; 9=flat).

While the results from the Farmer Participatory trial provide additional evidence supporting Oberkulmer Rotkorn and Elias as appropriate varietal choices for growing spelt and rye in North East England, the difference in yield results between the trials also highlights the potential risk of lodging in both crops. Significant lodging was not observed in the Nafferton field trial but was present in the FPT, especially in the second trial year. Both crop species are susceptible to lodging, especially the taller spelt varieties (Keller *et al.*, 1999; Konvalina *et al.*, 2010; Koutroubas *et al.*, 2012; Longin and Würschum, 2014) and when high levels of precipitation occur later in the season for rye (Peltonen-Sainio *et al.*, 2002; Peltonen-Sainio *et al.*, 2010b). Heavy rainfall in August of 2018 exposed lodging susceptibility in the taller varieties Oberkulmer Rotkorn (2.93), Rubiota (3.29) and Schlaegler (4.50) in the FPT (Table 3.3.3). Lodging in these varieties contributed to yield reductions and low Hagberg Falling Number, reflecting the risk associated with growing these taller varieties. While Oberkulmer Rotkorn and Elias were still the best yield-performing varieties, the Farmer Participatory trial shows that taking steps to reduce lodging risk, including sowing later in the season, sowing at a reduced seed rate, etc., may prevent yield and grain quality losses in spelt and rye.

It is also worth noting that rye establishment was problematic for all varieties at different locations in the Farmer Participatory trial. In 2017, rye varieties did not establish at all at two sites, and only one variety grew well enough for assessments at one site, while in 2018, rye did not establish at two sites and only two varieties grew at one site and three came through at another. This was largely due to late sowing in 2017 and sowing date and unreliable seed source in 2018. This issue in the FPT is also reflective of poor establishment in Schlaegler and Elvi in the NFT and demonstrates overall inconsistency in growing rye in the North East. Both trials also clearly show that rye was far more susceptible than spelt to slug damage (spelt is likely protected by its hull), which has implications for future rye growers, especially with the upcoming ban on the use of metaldehyde for slug control after April 2020 (DEFRA, 2018b).

The low rye yields in the Farmer Participatory trial reflect poor performance of OP (open pollinated) cultivars. European trials consistently demonstrate that hybrid rye varieties grown in favourable conditions produce higher yields than OP cultivars (Budzyński *et al.*, 2003; Hakala and Pahkala, 2003; Hansen *et al.*, 2004; Kunkulberga *et al.*, 2017). Although hybrid rye varieties were not included in either the NFT or FPT, three hybrid rye varieties supplied by breeders KWS UK were grown in strip plots at two sites during the second year of the Farmer Participatory trial. Because the hybrids were not included as trial replicates, results were not compared statistically, but observationally the hybrid varieties out-yielded the population cultivars included in the FPT. The hybrid rye varieties had an average yield of 5.2 t/ha and the highest yielding variety reached yields of 6.8 t/ha under conventional management. Despite this yield advantage, hybrid ryes have been out-yielded by OP varieties under adverse climatic conditions (Budzyński *et al.*, 2003; Hakala and Pahkala, 2003; Hansen *et al.*, 2004) and demonstrated poorer protein content compared with OP cultivars (Hansen *et al.*, 2004). The breeding efforts dedicated to hybrid rye development continue to improve overall performance and the yield and quality potential of hybrid rye varieties would certainly be worth considering in future UK trials.

Grain milling quality results in the Farmer Participatory trial reflected the patterns noted in the Nafferton field trial, as both Rubiota and Elias performed well across all parameters. The highest yielding spelt variety, Oberkulmer Rotkorn, had a lower HFN (216 seconds) than in the NFT (Table 7.4.2), but Falling Number was negatively affected by high August rainfall in 2018. Wet conditions during grain maturation has been shown to reduce HFN in both spelt (Lacko-

Bartošová *et al.*, 2010) and rye (McDonald, 1991; Hansen *et al.*, 2004; Salmenkallio-Marttila and Hovinen, 2005; Tupits, 2008; Kunkulberga *et al.*, 2017). Although low Falling Number is strongly influenced by climatic conditions, the rye variety that performed well in the Nafferton farm trial also had the highest HFN in both years of the FPT. Elias grain met the minimum milling recommendation for rye in 2017 (146 seconds) and had the highest HFN in 2018 (93 seconds), in a year when no rye grain met the minimum specification. In spelt, Rubiota HFN was more noticeably affected by wet conditions/lodging severity. The variety far exceeded the minimum specification for hard wheat (360 seconds) in 2017 and had the second highest falling number in 2018 (178 seconds). As noted for grain harvest, the Farmer Participatory trial exposed the risk of weather conditions affecting final yield and grain quality due to lodging and delayed harvest, which could be mitigated through later sowing and growing varieties with greater standing ability.

Table 7.4.2. Spelt and rye specific weight, protein content and Hagberg Falling Number (HFN) means by variety from the Nafferton field trial (NFT) and Farmer Participatory trial (FPT).

	Sp. Weight (kg/hl)		**Protein (%)**		**HFN (s)**	
Spelt	**NFT**	**FPT**	**NFT**	**FPT**	**NFT**	**FPT**
Filderstolz	75.5	77.7	13.2	13.3	255	256
Oberkulmer Rotkorn	74.2	77.2	14.8	14.9	230	216
Rubiota	76.2	78.0	14.8	14.8	259	262
ZOR	75.3	79.1	14.2	13.5	202	219
Rye						
Dankowskie Amber	70.4	70.6	9.14	11.2	97.5	121
Elias	71.3	71.0	8.77	10.7	126.6	118
Elvi	68.7	69.0	9.45	11.3	79.5	87
Schlaegler	66.9	66.9	10.30	12.2	90.2	90

Similar to the Nafferton field trial, the Farmer Participatory trial does not definitively recommend older varieties/landraces or modern genotypes based on both grain yield and grain quality parameters and care should be taken in drawing conclusions based on a limited number of varieties/landraces However, the same top-performing varieties in the NFT, Oberkulmer Rotkorn and Elias, also performed well in the FPT. The farmer-trial did emphasise the risks of climate affecting both yield and grain quality and the difficulties of establishing rye under non-ideal sowing conditions, but the same varieties displayed potential as alternative cereals for use in North East England.

7.4.3 MANAGEMENT SYSTEM

The Nafferton field trial was managed as a low-input non-organic system with the exception of a single herbicide application in both trial years to prevent confounding effects of weed competition. Fertiliser input types included organic fertilisers (biogas digestate, composted FYM and cattle slurry) and a conventional fertiliser (mineral N) but were applied at low rates (50 and 100 kgN/ha), as both spelt and rye are low nutrient-requiring crops. The Farmer Participatory trial established spelt and rye varieties on both organic and conventional farms to consider the effects of management on crop performance.

Crop yields were higher on non-organic farms compared to organic farms in the FPT. In non-organic systems, spelt yield was 3.15 t/ha and rye yield was 3.69 t/ha, compared to 2.18 t/ha for spelt and 2.23 t/ha for rye on organic farms. While each farm managed the trial individually (except for biogas digestate application on each site), only two organic sites applied any manure-based fertiliser, while the remainder did not apply any fertiliser (Table C.4., Appendix C). In contrast, all conventional farms, except one, applied at least one synthetic fertiliser during the trial (Table C.4., Appendix C). Fertility applications have been shown to increase yields in both spelt (Andruszczak *et al.*, 2011; Koutroubas *et al.*, 2012; Caldwell *et al.*, 2014) and rye (Nedzinskienė, 2006; Gollner *et al.*, 2011; Schlegel, 2014; Stepień *et al.*, 2016), and the results of the FPT demonstrate the benefit of fertiliser inputs in conventional systems. Coupled with the yield increase from biogas digestate application, the Farmer Participatory trial supports low-levels of fertiliser inputs to improve grain yields, in both organic and conventional management systems.

Farms included in the spelt and rye trial also differed in approaches to crop protection. All organic farms did not apply any herbicide or fungicide, following certification standards, while all but one conventional site was treated with at least one herbicide and one fungicide during the trial (Table C.5., Appendix C). The primary diseases in the FPT were yellow striped rust (*Puccinia striiformis*) in spelt and brown leaf rust (*Puccinia recondita*) in rye, diseases that can be effectively controlled with fungicides (Chen, 2005; Schlegel, 2014). Conventional farms clearly have an advantage when it comes to disease management, which likely contributes to yield differences, although varieties noted for disease resistance (mainly the spelt landrace Oberkulmer Rotkorn) had high yields across all farms. The Farmer Participatory trial shows that fungicide applications can be beneficial to spelt and rye yield in conventional systems and that selecting for disease resistance can provide a yield advantage under organic management and is a key strategy to maintain crop performance in conventional systems facing increasing levels of fungicide resistance.

7.5 ECONOMIC VIABILITY

As minor cereal crops, the market for spelt and rye in the UK is not exceptionally well documented, though consumer interest due to perceived (and documented) health benefits continues to grow. Both species have strong profitability potential; high-quality grains for artisan bread-making are considered premium products and low-input costs can contribute to net gains. While this may be encouraging for growers looking to diversify their cropping system, the specific input and outputs for both spelt and rye are worth considering to evaluate the economic viability of these minor cereals.

Spelt is often marketed for organic management systems, due to yield potential under low-input fertility and the protection from pests, disease, nutrient loss and degradation provided by its hull (Bonafaccia *et al.*, 2000). The same hull also adds additional processing requirements post-harvest to clean the grain (Arzani and Ashraf, 2017), which contributes final grain losses (Lacko-Bartošová *et al.*, 2010) and additional expense (Stallknecht *et al.*, 1996). Yield losses are expected to be 25-30% due to processing and though de-hulling charges vary based on specific contracts, in North East England they can be upwards of £180/tonne (A. Wilkinson, pers. comm.). Despite this additional cost, the price for organic de-hulled grain, especially of high milling quality, is much higher than for commercial wheat. In 2018, organic milling wheat received £315/tonne (Soil Association, 2018), while milling-quality de-hulled spelt received £850-950/tonne depending on specific contracts (A. Wilkinson, pers. comm.). The market for conventionally-grown spelt is not as well documented and is considered generally weak, while the market for organic spelt is consistently strong (Caldwell *et al.*, 2014).

Based on Oberkulmer Rotkorn yields and typical management from the Farmer Participatory trial, the Gross Margin for hulled spelt is £337/ha in organic production and £191/ha in conventional production while the margin for de-hulled organic spelt is £426/ha (Table 7.5.1). The margins re-emphasise the preference for growing spelt in organic systems, as the lower yields in conventional systems do not outweigh the savings on fertiliser and crop protection costs and de-hulled spelt achieves a much higher premium, especially organically, which offsets some of the additional costs and yield loss associated with processing. These returns are based on yields for Oberkulmer Rotkorn as the highest-yielding variety but includes data from many farms with varied management practices, including no fertiliser input on many organic farms, which will certainly impact specific margins. There is every expectation that with low-cost fertility applications, a full commercial field of spelt would produce higher yields and achieve higher margins than presented in this example.

Table 7.5.1. Gross margins for organic and conventional spelt production based on Oberkulmer Rotkorn performance in the Farmer Participatory trial.

	Organic (ex-farm)	**Organic (de-hulled)**	**Conventional (ex-farm)**
Variable Costs	**£/ha**	**£/ha**	**£/ha**
Seed	£270	£270	£270
Fertiliser	£35	£35	£170
Sprays			£200
Fixed Costs			
Plough	£60	£60	£85
Combination drill	£60	£60	£50
Processing Costs			
Haulage (£35/t)		£78.40	
De-hulling (£180/t)		£403.20	
Total Costs	**£425**	**£906.60**	**£775**
Outputs			
Yield t/ha	2.24	1.57[+]	3.22
Price £/t	£340	£850	£300
Gross Yield	**£761.60**	**£1332.80**	**£966.00**
Gross Margin	**£336.60**	**£426.20**	**£191.00**

[+]De-hulled yield estimated as 30% loss from hulled yield.
All costs/prices for spelt production estimated based on the Organic Farm Management Handbook (Lampkin *et al.*, 2017), the John Nix Farm Management Pocketbook (Redman, 2019) and expectations for high-quality milling (A. Wilkinson, pers. comm.). Prices/costs vary by year and according to contracts.

Rye is not as closely associated with organic management systems as spelt, but it is valued for an ability to grow in poor climatic and soil conditions, including low-fertility (Bushuk, 2001; Deike *et al.*, 2008; Schlegel, 2014). Prices for milling quality rye are based on meeting quality specification for baking, especially for crispbreads, and the demand for UK-grown rye is currently low due to import competition from mainland Europe and Canada (Redman, 2019). As with most cereals, organic rye does attract a higher premium, especially as good quality milling grain (Lampkin *et al.*, 2017).

Elias was the highest yielding and only variety that consistently met milling specifications in the Nafferton field trial and Farmer Participatory trials. Based on yields and management from the FPT, the Gross Margin is £474/ha in organic production and £283/ha in conventional production for milling-quality rye sold ex-farm (Table 7.5.2). Again, the margins emphasise suitability for low-input/organic systems in terms of cost savings and the organic premium, especially considering the lower yields produced in the trial. Establishment and slug damage limited rye productivity in the FPT and considering rye's potential to reach yields of 7 t/ha in the UK (Redman, 2019), there is room to improve yields, and margins, under conventional management.

Table 7.5.2. Gross margins for organic and conventional rye production based on Elias performance in the Farmer Participatory trial.

	Organic (ex-farm)	Conventional (ex-farm)
Variable Costs	**£/ha**	**£/ha**
Seed	£99	£95
Fertiliser	£39	£146
Sprays		£110
Fixed Costs		
Plough	£60	£85
Combination drill	£60	£50
Total Costs	**£258**	**£486**
Outputs		
Yield t/ha	2.44	4.81
Price £/t	£300	£160
Gross Yield	**£732.00**	**£769.60**
Gross Margin	**£474.00**	**£283.60**

All costs/prices for rye production estimated based on the Organic Farm Management Handbook (Lampkin *et al.*, 2017) and the John Nix Farm Management Pocketbook (Redman, 2019). Prices/costs vary by year and according to contracts.

Although the specific costs and prices for spelt and rye vary depending on individual management practices and annual fluctuations, the estimated Gross Margins for the highest yielding spelt and rye varieties demonstrate economic viability of these varieties, especially for organic management. The calculations also do not account for the environmental, crop diversity and nutritional benefits attributed to both spelt and rye as minor cereals, among additional factors that play into crop selection and management decisions.

7.6 FUTURE RESEARCH

The spelt and rye trials focused on fertiliser treatment and variety choice in both the Nafferton field trial and Farmer Participatory trial. These trials effectively evaluate the performance of alternative fertilisers and minor cereal genotypes in Northeast England, but also highlight areas for future improvement and research focus.

In small-plot based field trials, there is certainly more to be gained from trialling additional spelt and rye varieties and fertility regimes. Considering trends in both spelt and rye across the full four years of the trial, differences between landraces and modern genotypes of both species stood out. The spelt landrace, Oberkulmer Rotkorn, was the top-performing spelt and the old Austrian variety Schlaegler was one of the poorest performing rye varieties. Including an equal number of modern and landrace varieties in future trials would provide additional insight into how breeding affects the productivity and baking/nutritional quality of minor cereals. Hybrid ryes have become increasingly popular in the UK and comparing hybrids with milling-quality rye genotypes would help identify characteristics of rye varieties with improved yield potential in North East UK climate conditions.

Biogas digestate was the stand-out fertiliser input type of both the Nafferton field trial and Farmer Participatory trial, producing yields that matched or exceeded results from mineral N applications. Digestate is applied in the spring, along with mineral N and cattle slurry, while composted organic fertilisers are autumn-applied inputs. A trial of spring-based fertility applications would also be illuminating, with more variation in application rates and timings to identify an ideal fertility regime for low-input crops. Neither spelt nor rye requires high nutrient inputs, but staggering applications dates/rates would provide additional insight into how fertility can be maximised in these minor crops.

Although rye was largely unaffected by leaf disease, spelt disease severity varied significantly by variety and likely contributed to lower yields in the spelt x wheat cross, Filderstolz. Especially considering the prevalence of yellow rust in both the Nafferton field trial and Farmer Participatory trial, including fungicides as a response variable would provide an indication of spelt variety suitability for conventional production systems. The threat of ergot in rye is an additional factor that should be considered more closely, including through analyses post-harvest to test for ergot contamination, to identify varieties with lower susceptibility and effective management practices.

The FPT identified sowing date as a potential mitigating factor against yield and quality losses due to lodging in taller-stemmed varieties and poor establishment in rye. Sowing date was consistent in the Nafferton field trial but could be used as a factor in future trials. Farmer participatory trials within the same region can also be managed to have sowing dates within a week of another to avoid confounding effects or repeat trials in the same field on different dates to include sowing date as a factor. The risks of lodging are based primarily on stem height and climatic conditions but identifying the role that later sowing can have on mitigating this risk would be valuable. Additionally, rye establishment was problematic in both trials, which may be improved by varying sowing date, especially as an adjustment to wet and cold conditions.

The FPT not only evaluated the same spelt and rye varieties that were in the Nafferton field trial but also served as a pilot study to determine how best to set-up and manage a study across multiple farm sites. The recruitment process and use of the online database show the potential for participatory trials that provide farmers with useful experience and information while maintaining high research-quality data management standards. The chapter also noted that there was room for improvement, including involving farmers earlier in the research-design process and providing training for using the online database. In terms of the literal management of the on-farm trials, discrepancies in how the varieties were sown occurred because farmers were asked to sow seed individually. While there is certainly value to comparing how crops perform on different farms based on each farmers specific management techniques, consistent sowing, including seed-bed preparation, sowing rates and dates are only guaranteed if managed directly by the research team. Future trials will need to clearly identify the primary desired outcomes and consider which specific management requirements should be left to participants and which are best arranged by researchers. The spelt and rye trial demonstrated that farmer interest and database management technology is available to support a farmer participatory trial network in North East England and will hopefully continue to be implemented in the future.

APPENDIX A

Climate Data

Table A.1. Mean daily air temperature, monthly radiation and monthly rainfall for the spelt and rye field trials at Nafferton farm over the experimental period (2014-2016).

	Mean air temp (°C)		**Total Radiation (MJ/m^2)**		**Total Rainfall (mm)**	
	2014/15	**2015/16**	**2014/15**	**2015/16**	**2014/15**	**2015/16**
September	13.26	11.18	242.76	275.53	26.4	38.4
October	11.55	9.71	45.03	143.21	21.2	58.8
November	7.95	8.18	29.50	52.25	51.0	117.4
December	4.36	7.85	26.25	25.42	62.4	161.6
January	3.48	4.72	46.48	36.92	50.4	149.4
February	3.61	3.73	109.91	121.92	25.0	34.4
March	5.15	5.46	225.25	220.42	58.0	27.8
April	7.54	6.14	462.18	321.14	27.4	50.8
May	8.97	10.68	482.36	170.51	77.6	21.4
June	12.35	12.72	513.49	454.16	29.8	88.0
July	13.72	15.39	479.17	396.27	133.6	63.6
August	14.59	15.19	451.10	434.78	79.2	66.4
Annual Mean/Total+	8.87	9.25	3113	2653	642	878

+All values in this row are means for the year period labelled in the columns excepting the Radiation and Rainfall columns, which are total amounts during the year.
NB: Due to technical faults, climatic records were not recorded for the following time periods: 8 Oct 2014 to 19 Oct 2014, 21 Nov 2014 to 26 Nov 2014, 30 Dec 2014 to 5 Jan 2015, 29 April 2016 to 19 May 2016.

Table A.2. Long-term averages for mean daily air temperature, monthly rainfall and monthly radiation at the Durham weather station from 1981-2010*.

	Mean air temp (°C)	**Radiation (MJ/m^2)**	**Rainfall (mm)**
January	4.14	60.40	49.24
February	4.43	116.41	44.14
March	6.09	236.98	37.83
April	8.45	345.17	50.73
May	11.04	434.81	36.24
June	13.98	420.99	60.02
July	15.71	438.05	78.98
August	15.70	338.01	57.23
September	13.71	239.75	45.86
October	10.15	142.82	59.91
November	6.81	74.51	75.41
December	3.58	49.71	51.85

All data from the MetOffice Durham Weather Station (54:77 N, 01:58 W, 102m above sea level), located 31.5 km from Nafferton Farm (54:59 N; 1:54: W, 117m above sea level).
*Global radiation data was only available beginning from September 1999, therefore radiation means are for the period from September 1999 through 2010.

Table A.3. Mean daily air temperature, monthly radiation and monthly rainfall recorded at Nafferton farm over the Farmer Participatory trial period (2016-2018).

	Mean air temp (°C)		**Total Radiation (MJ/m^2)**		**Total Rainfall (mm)**	
	2016/17	**2017/18**	**2016/17**	**2017/18**	**2016/17**	**2017/18**
September	14.75	12.35	271.70	229.45	52.8	84.4
October	9.76	11.47	137.52	120.72	57.4	51.4
November	4.60	5.72	66.05	66.59	95.0	69.6
December	6.63	4.14	29.18	35.26	38.2	56.4
January	4.35	4.15	43.16	46.02	30.8	77.0
February	5.56	2.36	91.32	115.97	62.8	45.6
March	7.39	3.71	241.17	204.53	75.6	100.4
April	7.95	8.11	381.78	320.18	14.8	67.6
May	11.90	11.99	507.99	579.63	19.8	31.0
June	14.43	14.17	465.28	560.46	127.2	33.8
July	14.42	16.94	429.11	557.52	68.4	25.2
August	14.66	15.29	407.93	365.48	31.6	108.6
Annual Mean/Total+	9.7	9.2	3072.19	3201.81	674.4	751

+All values in this row are means for the year period labelled in the columns excepting the Radiation and Rainfall columns, which are total amounts during the year.
NB: Due to technical faults, temperature was not recorded from 15-18 June 2018.

APPENDIX B

Database Management System

Table B.1. Full data-dictionary for the Farmer Participatory trial online database system.

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Farm Background									
Geographic Location									
Farm Name	Name of Farm Business	Will be used to refer to specific trial site	Text	N/A	Full farm name (no abbreviations)	Once	Farmer		Cell needs to be filled to identify specific farm
Post Code	Farm address postcode	Identify farm location	Text	N/A	e.g. NE43 7XD	Once	Farmer	Should fall within county	Empty cells filled manually using farm name
Elevation	Location of farm relative to sea level (m above sea level)	Allow for comparisons between farm elevations	Numeric	m above sea level	Numbers	Once	Researcher		Empty cells filled manually using farm location
Farm Description (General descriptors of participating farm)									
Farm Size	Area of farm site	Allow for size-based comparisons	Numeric	ha	Numbers	Annual	Farmer	Should be at least same size or larger than field size	
Farm Type	Characterisation of farm, eg arable, dairy, mixed	Allow for comparison between types	Text	N/A	Option to select from list (arable, mixed, dairy, other with entry field)	Annual	Farmer	Mixed/dairy should have livestock and manure	
Presence of Livestock	Identify presence or absence of livestock	Determine whether or not waste materials are produced and managed on-site	Categorical	N/A	YES or NO	Annual	Farmer	Presence of livestock will require additional descriptions of type and stocking rate	Assume NO unless type and stocking rate are complete, then YES

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Farm Background (cont)									
Farm Description (cont) (General descriptors of participating farm)									
Presence of Livestock	Identify presence or absence of livestock	Determine whether or not waste materials are produced and managed on-site	Categorical	N/A	YES or NO	Annual	Farmer	Presence of livestock will require additional descriptions of type and stocking rate	Assume NO unless type and stocking rate are complete, then YES
Livestock Type(s)	Identify type of livestock on farm	Distinguish further between types of waste on farm	Text (dropdown list)	N/A	Up to 5 fields available to enter text (e.g. beef cattle, dairy cattle, sheep, etc.)	Annual	Farmer	Fields should be complete if livestock response is YES	Empty fields are expected if livestock response is NO
Stocking Rate(s)	Number of animals per hectare on farm	Determine how much waste expected on site	Numeric	head/ha	Number of fields corresponds to number of types	Annual	Farmer	Fields should be complete if livestock response is YES	Empty fields expected if livestock response is NO
Presence of Manure	Identify presence or absence of manure	Determine if fertiliser source is available and managed on-site	Categorical	N/A	YES or NO	Annual	Farmer	Should be complete if livestock response is YES	No data expected if livestock response is NO
Manure Processing Method	Identify how manure is treated/used	Determine what type of fertiliser sources may be produced on-site	Text (dropdown list)	N/A	Up to 3 fields available to enter text (e.g. windrow composting, slurry tank, anaerobic digestion, etc.)	Annual	Farmer	Should be complete if manure response is YES	No data expected if manure response is NO
Additional Details	Opportunity to include any other information	Additional information may be useful but unidentified at this point	Text	N/A	Box for any type of information/description	Annual	Farmer		Missing data expected most of the time

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Typical Farm Management (should be reflective of previous 5 years and fields should be updated annually)									
Management System	Identify whether conventional or organic management	Allow for management type comparisons	Text (dropdown list)	N/A	Option to select from drop down list (Organic-Certified, Conventional, Organic-Not Certified)	Annual	Farmer	Weeding Protocols will vary based on management type	
Crop Rotation Length	Length of time to complete a full rotation	Identify long/short rotation farms	Numeric	Years	Whole Numbers	Annual	Farmer	Number of years should correspond to list length of crop rotation	Empty cells can be filled manually using crop rotation list length
Crop Rotation	Order of current crop rotation	Describes farm management plan	Text	N/A	Ordered list (e.g. winter wheat, winter barley, winter oilseed rape, winter wheat, potatoes)	Annual	Farmer	List length should correspond to crop rotation length	
Fertiliser Type(s)	Identify primary fertiliser inputs used on farm	Describes farm management plan	Text	N/A	Up to 5 fields available to enter text (e.g. fresh manure, compost, mineral N, etc.)	Annual	Farmer	Number of fields should correspond to number of fields for rate	
Fertiliser Rate(s)	Identify how much fertiliser is applied	Describes farm management and typical fertiliser applications	Numeric	kg/ha	Number of fields corresponds to number of types	Annual	Farmer	Number of fields should correspond to number of fields for type	
Fertiliser Timing(s)	Identify when fertiliser is applied	Describes farm management and typical fertiliser applications	Text	N/A	Approximate date (day-month) of fertility applications	Annual	Farmer	Number of fields should correspond to number of fields for type and rate	

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Typical Farm Management (cont) (should be reflective of previous 5 years and fields should be updated annually)									
Synthetic Crop Protection?	Identify whether herbicides/insecticides/fungicides are used or not	Identifies which farms will have spray data and which will not	Categorical	N/A	YES or NO	Annual	Farmer	Farms identified as conventional will likely answer YES; organic should answer NO	Empty cells can be filled based on management type response and/or responses to following questions
Crop protection type(s)	Identify applications	Describes farm management plan	Text	N/A	Up to 3 fields available to enter text (e.g. fluroxypyr, glyphosate)	Annual	Farmer	Fields should be complete if crop protection response is YES	Empty cells expected if crop protection response is NO
Crop protection rate(s)	Identify how much applied	Describes farm management and typical applications	Numeric	L/ha	Number of fields corresponds to number of types	Annual	Farmer	Number of fields should correspond to number of fields for types	Empty cells expected if crop protection response is NO
Crop protection timing(s)	Identify when applied	Describes farm management and typical applications	Text	N/A	Approximate date (day-month) of applications	Annual	Farmer	Number of fields should correspond to number of fields for type and rate	Empty cells expected if crop protection response is NO
No-Chem Weed control?	Identify whether non-chemical weed control methods employed	Identifies which farms will have weed control data and which will not	Categorical	N/A	YES or NO	Annual	Farmer	Farms identified as organic more likely to answer YES but conventional farms may use more than just pesticide	Empty cells can be filled based on responses to the following questions
Weed control type(s)	Identify primary weed control methods	Describes farm management and typical weed control	Text	N/A	Up to 3 fields available to enter text (e.g. hand-weeding, tine-weeding)	Annual	Farmer	Fields should be complete if weed control response is YES	Empty cells expected if weed control response is NO

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Typical Farm Management (cont) (should be reflective of previous 5 years and fields should be updated annually)									
Weed control timings	Identify when weed control takes place	Describes farm management and typical weed control	Text	N/A	Approximate date(day-month) weed control took place	Annual	Farmer	Fields should be completed if weed control response is YES	Empty cells expected if weed control response is NO
Tillage system	Identify primary tillage practices	Describes farm management and typical tillage practices	Text	N/A	Up to 3 fields available to enter text (e.g. none, min-til, intensive, conservation)	Annual	Farmer		
Additional Management	Opportunity to include any other information	Additional information may be useful but unidentified at this point	Text	N/A	Box for any type of information/description	Annual	Farmer		Missing data expected most of the time
Experimental Field Data Inputs (specific to field trial site)									
Field Background									
Soil type	Basic soil type descriptors	Describes field site conditions	Text (dropdown list)	N/A	Example (permeable clay loam)	Annual	Researcher		Empty cells can be filled by using Soilscape to identify approximate type from UK map
Gradient	Measure of land angle/slope	Describes field site conditions	Numeric	Degrees	Numbers	Annual	Researcher		
GPS	Specific location of experimental field	Coordinates can be used to pinpoint location on a map	Text	N/A	Two fields, one for lat. one for long. Example (54:59:26.3 N; 1:54:37.4 W)	Annual	Researcher		
Orientation	Direction field faces	Describes field site conditions	Text	N/A	Example (south-facing)	Annual	Researcher		

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Experimental Field Data Inputs (cont)(specific to field trial site)									
Field Background (cont)									
Size	Overall size of experimental field	Describes field site	Numeric	ha	Numbers	Annual	Researcher		If specific field location is known on map, can use MAGiC or DigiMaps to estimate area
Previous Crop	What was grown in field during previous year	Describes field site conditions	Text	N/A	Example (Spring barley)	Annual	Farmer		
Trial Management (records of dates and rates of management applied to experiment field during trial)									
Trial Species	Crops being sown as part of trial	Allows for collecting data on different crops separately	Text (dropdown list)	N/A	Example (Spelt OR Rye)	Annual	Researcher		
Trial Varieties	Varieties of each crop begins sown as part of trial	Allows for collecting data on different varieties separately	Text	N/A	List (e.g. Rubiota, ZOR, Oberkulmer Rotkorn)	Annual	Researcher	The number of entries in this field will impact data entry for all the following fields--there should be a separate set of entries for each variety	
Sowing Date	Date trial sown	Allows for sowing date to be included as a factor	Number (date)	N/A	Date (day-month) trial was sown	Annual	Farmer	Number of possible fields will depend on the number of varieties	

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Trial Management (cont) (records of dates and rates of management applied to experiment field during trial)									
Seed Rate	Seeding rate--amount of seeds per area	Allows for seeding rate to be included as a factor (and checked against recommended values)	Text	kg/ha	Numbers	Annual	Farmer	Number of possible fields will depend on the number of varieties	
Fertiliser Type(s)	Identify fertiliser inputs included in trial	Records fertiliser inputs to be included as factors	Text	N/A	Up to 3 fields available to enter text (e.g. fresh manure, compost, mineral N, etc.)	Annual	Farmer	Number of fields should correspond to number of fields for rate	
Fertiliser Rate(s)	Identify how much fertiliser is applied to experiment	Records fertiliser rates to be included as factors	Numeric	kg/ha	Number of fields corresponds to number of types	Annual	Farmer	Number of fields should correspond to number of fields for type	
Fertiliser Timing(s)	Identify when fertiliser is applied to experiment	Records fertility application timing as factor	Text	N/A	Date (day-month) of fertility applications	Annual	Farmer	Number of fields should correspond to number of fields for type and rate	
Synthetic Crop Protection?	Identify whether herbicides/insecticides/fungicides are used or not	Identifies which farms will have chemical crop protection data and which will not	Categorical	N/A	YES or NO	Annual	Farmer	Farms that answer YES will enter data in follow fields relating to crop protection	

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Trial Management (cont) (records of dates and rates of management applied to experiment field during trial)									
Crop protection type(s)	Identify applications	Records chemical crop protection application as a factor	Text	N/A	Up to 3 fields available to enter text (e.g. fluroxypyr, glyphosate)	Annual	Farmer	Fields should be complete if crop protection response is YES	Empty cells expected if crop protection response is NO
Crop protection rate(s)	Identify how much is applied	Records rates as factors	Numeric	L/ha	Number of fields corresponds to number of types	Annual	Farmer	Number of fields should correspond to number of fields for types	Empty cells expected if crop protection response is NO
Crop protection timing(s)	Identify when pesticides applied	Records application timings as factors	Text	N/A	Date (day-month) of pesticide applications	Annual	Farmer	Number of fields should correspond to number of fields for type and rate	Empty cells expected if crop protection response is NO
No-Chem Weed control?	Identify whether non-chemical weed control methods employed	Identifies which farms will have weed control data and which will not	Categorical	N/A	YES or NO	Annual	Farmer	Farms that answer YES will enter data in follow fields relating to weed control	
Weed control type(s)	Identify weed control methods	Records weed control as a factor	Text	N/A	Up to 3 fields available to enter text (e.g. hand-weeding, tine-weeding)	Annual	Farmer	Fields should be complete if weed control response is YES	Empty cells expected if weed control response is NO

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Trial Management (cont) (records of dates and rates of management applied to experiment field during trial)									
Weed control timings	Identify when weed control takes place	Records weed control timing as a factor	Text	N/A	Date(day-month) weed control took place	Annual	Farmer	Fields should be completed if weed control response is YES	Empty cells expected if weed control response is NO
Tillage	Identify tillage practices	Records tillage as a factor	Text	N/A	Up to 3 fields available to enter text (e.g. none, min-til, intensive, conservation)	Annual	Farmer		
Experimental Assessment Inputs (each data entry recording should have date of measurement field as well)									
Soil Assessments (samples taken prior to planting and potentially at intervals during trial)									
pH	Soil pH	Record of soil status during trial	Numeric	N/A	Number	Many	Researcher		Empty cells can be filled using means from plots with the same treatments
N	N concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
P	P concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
K	K concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
Fe	Fe concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
Mn	Mn concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Experimental Assessment Inputs (cont) (each data entry recording should have date of measurement field as well)									
Soil Assessments (cont) (samples taken prior to planting and potentially at intervals during trial)									
Zn	Zn concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		Empty cells can be filled using means from plots with the same treatments
Cu	Cu concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
Boron	Boron concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
Hg	Hg concentration in soil	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
Other Heavy Metals	Space for additional heavy metal concentrations to be included	Record of soil status during trial	Numeric	mg/kg	Number	Many	Researcher		
Crop Growth Assessments (date recorded for every assessment)									
Emergence	Count of the number of plants emerging on a specific date	Records success of germination and can compare to number of plants after harvest	Numeric	plants/m^2	Whole Numbers	Annual	Researcher		Empty cells can be filled using means from plots with the same treatments
Tiller count	Count of the number of stems on each plant on specific date	Records expected number of stems to be compared to number after harvest	Numeric	stems/m^2	Whole Numbers	Annual	Researcher		

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system									
Field Name	**Description**	**Justification**	**Data Type**	**Units**	**Formatting**	**Frequency**	**Recorder**	**Relationships**	**Missing Data**
Experimental Assessment Inputs (cont) (each data entry recording should have date of measurement field as well)									
Crop Growth Assessments (cont)									
GS31 Date	Date Growth Stage 31 is reached (stem extension)	Tracks plant progress and speed of development	Number (date)	N/A	Date (day/month)	Annual	Researcher		Empty cells can be filled using means from plots with the same treatments
GS39 Date	Date Growth Stage 39 is reached (Flagleaf emergence)	Tracks plant progress and speed of development	Number (date)	N/A	Date (day/month)	Annual	Researcher		
GS62 Date	Date Growth Stage 62 is reached (Anthesis)	Tracks plant progress and speed of development	Number (date)	N/A	Date (day/month)	Annual	Researcher		
Weed density	Percent ground cover of weeds in m^2	Records presence of weeds	Numeric	%	Whole Numbers	Many	Researcher		
Weed composition	Top 3 weeds present	Records types of weeds	Text	N/A	List(e.g. meadow grass, thistle, cleavers)	Many	Researcher	Number of recordings will match number for weed composition	
Plant height	Average plant height at specific GS	Records plant growth	Numeric	cm	Whole Numbers	Many	Researcher	Number of recordings will match number for weed density	

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Experimental Assessment Inputs (cont) (each data entry recording should have date of measurement field as well)									
Crop Growth Assessments (cont)									
SPAD	Measure of leaf chlorophyll content, which reflects plant N content	Tracks changes in N content in the plant during growing season	Numeric	N/A	Average of multiple recordings	Many	Researcher		Empty cells can be filled using means from plots with the same treatments
Disease score	Score of leaf/ear cover affected by disease	Tracks presence and progress of diseases	Numeric	N/A	Whole Numbers	Many	Researcher		
Lodging	Percent of area experiencing lodging	Records presence and severity of lodging	Numeric	%	Whole Numbers	Many	Researcher		
Grain Harvest Assessments									
Harvest Date	Date of harvest	Tracks when crops were collected	Text	N/A	Date (day/month)	Annual	Researcher		
Combine Yield	Grain fresh weight as measured straight off the combine	Quantifies yield as it is coming off the field	Numeric	kg	Numbers	Annual	Researcher		Empty cells can be filled using means from plots with the same treatments
Sub-sample FW Yield	Fresh Weight Subsample taken from total combined to complete further analysis	Records grain amount included in subsample	Numeric	g	Numbers	Annual	Researcher	Will be less than total combinable yield	

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Biomass Harvest Assessments									
Sub-sample DW Yield	Subsample from total combined after oven drying	Records grain amount in subsample after drying--can calculate % dry and moisture	Numeric	g	Numbers	Annual	Researcher	Will be less than SS FW Yield amount	Empty cells can be filled using means from plots with the same treatments
Moisture %	Grain moisture content calculated from sub-sample FW and DW	Measure moisture content at harvest	Numeric	%	Numbers	Annual	Researcher	Calculated from SS FW Yield and SS DW Yield	
Plant Number	Number of plants collected along m strip	Can be used to consider how many plants resulted in specific yield	Numeric	plants/m	Whole numbers	Annual	Researcher	Will be less than the number of stalks	
Tiller Number	Number of tillers within m strip biomass collection	Can be used to consider how many tillers were collected per plant and per ear	Numeric	stalks/m	Whole Numbers	Annual	Researcher	Will be more than the number of plants and more or equal to the number of ears	
Tiller Weight	Weight of tillers collected at biomass harvest	Record of sample tiller weight	Numeric	g	Numbers	Annual	Researcher		

Table B.1. (cont) Full data-dictionary for the Farmer Participatory trial online database system

Field Name	Description	Justification	Data Type	Units	Formatting	Frequency	Recorder	Relationships	Missing Data
Grain Quality Assessments									
Ear Number	Number of ears with m strip biomass collection	Can be used to consider how many ears were produced per plant	Numeric	ears/m	Whole Numbers	Annual	Researcher	Will be less than or equal to the number of stalks	Empty cells can be filled using means from plots with the same treatments
Ear Weight	Weight of ears collected at biomass harvest	Record of sample ear weight	Numeric	g	Numbers	Annual	Researcher		
1000 grain weight	Weight of 1000 grains	Used as a measure of seed size to help identifying sowing rates	Numeric	g	Numbers	Annual	Researcher		
Specific Weight	Grain weight that can be packed into a fixed volume cylinder	Shrivelled grain will not mill well-- specific weight helps identify grain shape	Numeric	kg/hL	Numbers	Annual	Researcher		
Protein DM	Percent protein in dry matter grain sample	Protein is a measure for identifying baking quality of flour	Numeric	%	Numbers	Annual	Researcher		
Hagberg Falling Number	Time it takes disc to fall through heated flour-water mixture (includes 60 seconds of stirring)	Estimate of alpha-amylase activity	Numeric	seconds	Whole Numbers	Annual	Researcher		

Table B.2. Crop management details for rye grown in various Estonian farms

Farm	Management	Soil type	Pre-crop	Gradient	Area ha	Variety	Sowing Date	Sowing rate
Lalluka	organic	Eutric Cambisol,	barley	plane	3.2	Elvi	12.09.	125
Jogeva county		sandy loam		58°42'34.6"N		Elias	12.09.	147
				26°22'52.9"E		Vambo	12.09.	97
				E–W		D.Amber	12.09.	125
Valjaotsa	organic	Umbri-Luvic Gleysol,	barley	plane	4.2	Elvi	13.09.	125
Ida-Viru		loamy sand		58°99'189"N		Elias	13.09.	147
county				26°88'609"E		Sangaste	13.09.	109
				S–N		D.Amber	13.09.	125
Erto Farm	organic	Gleyic Luvisol,	pea	slight incline	3.7	Elvi	14.09.	125
Jogeva county		sandy loam		58°37'204"N		Elias	14.09.	147
				26°42'420"E		Sangaste	14.09.	109
				E–W		D.Amber	14.09.	125
Rebasmae Farm	organic	Cutanic Luvisol,	grassland	plane	23.3	Elvi	15.09.	125
Rapla county		loamy sand		59°08'731"N		Elias	15.09.	147
				24°41'604"E		Sangaste	15.09.	109
				S–N		D.Amber	15.09.	125
Voore Farm	conventional	Eutric Cambisol,	barley	plane	36.9	Elvi	13.09.	125
Laane-Viru		sandy loam		59°12'023"N		Elias	13.09.	147
county				26°29'321"E		Sangaste	13.09.	109
				W–E		D.Amber	13.09.	125
Rannu Seeme	conventional	Eutric Calcaric Cambisol,	rape seed	slight incline	4.5	Elvi	14.09.	125
Tartu county		sandy loam		58°14'545"N		Elias	14.09.	147
				26°16'135"E		Vambo	14.09.	97
				E–W		D.Amber	14.09.	125
Estonia	conventional	Eutric Gleysol,	barley	plane	16.0	Elvi	15.09.	125
Jarva county		sandy loam		58°45'724"N		Elias	15.09.	147
				25°32'908"E		Vambo	15.09.	97
				E–W		D.Amber	15.09.	125
Kulmsoo	conventional	Stagnic Luvisol,	grass	slight incline	4.0	Elvi	22.09.	125
Polva county		loamy sand		58°02'261"N		Elias	22.09.	147
				26°55'496"E		Vambo	22.09.	97
				N–S		D.Amber	22.09.	125

Table B.2. (cont.) Crop management details for rye grown in various Estonian farms.

ETKI/Farm	Fertiliser type / rate ETKI			Fertiliser type / rate FARM			Soil cultivation	Crop protection	Weed control
	dig./slur.	manure	mineral	dig./slur.	manure	mineral			
Lalluka	50 kg N ha 27/04/2017	-	-	-	-	-	min tillage	-	mechanical before sowing
Valjaotsa	50 kg N ha 28/04/2017	-	-	-	75 kg N ha 09/09/2016	-	min tillage	-	mechanical before sowing
Erto Farm	50 kg N ha 27/04/2017	-	-	-	50 kg N ha 12/09/2016	-	min tillage harrowing	-	mechanical before sowing
Rebasmae Farm	50 kg N ha 27/04/2017	-	-	-	50 kg N ha 12/09/2016	-	ploughing min tillage	-	mechanical before sowing
Voore Farm	-	-	50 kg N ha 28/04/2017	70 kg N ha 28/08/2016	-	70 kg N ha 9/04/2017 20/04/2017	surface min tillage	-	Biathlon 4D 60g/ha 28/08/2016 15/05/2017
Rannu Seeme	50 kg N ha	-	50 kg N ha 27/04/2017	-	-	15 kg N ha 20/08/2016	ploughing breaking up	-	Sekator OD 1l/ha glyphosate 20/08/2016 05/05/2017
Estonia	-	-	50 kg N ha 28/04/2017	60 kg N ha 29/08/2016	-	-	min tillage	-	Sekator OD 1l/ha 22/08/2016 08/05/2017
Kulmsoo	-	-	50 kg N ha 27/04/2017	-	70 kg N ha 21/09/2016	50 kg N ha 9/04/2017	min tillage	-	MCPA 1 l/ha glyphosate 3 l/ha 29/08/2016 02/05/2017

Table B.3. Soil mineral properties for Estonian Farmer Participatory trial sites in 2016-17.

		pH	N %	P mg/kg	K mg/kg	Ca mg/kg	Mg mg/kg	Mn mg/kg	Cu mg/kg	B mg/kg	Fe mg/kg	Hg mg/kg	Pb mg/kg	Cd mg/kg
Lalluka	org	6.7	0.21	81	145	2401	164	124	1.3	0.88	8870+/-2220	0.020+/-0.005	6.60+/-1.65	0.083+/-0.021
Valjaotsa	org	5.8	0.17	22	58	1337	98	27	0.8	0.34	5160+/-1290	0.031+/-0.008	4.96+/-1.24	0.046+/-0.012
Erto Farm	org	6.8	0.24	295	247	2596	148	107	2.0	1.16	9400+/-2350	0.026+/-0.007	6.35+/-1.59	0.102+/-0.030
Rebasmae Farm	org	5.6	0.2	26	162	1634	164	136	0.9	0.76	11540+/-2885	0.024+/-0.006	9.17+/-2.29	0.102+/-0.030
Voore Farm	con	7.2	0.22	42	338	3085	574	330	1.4	1.48	14900+/-3725	0.022+/-0.006	10.0+/-2.50	0.075+/-0.019
Rannu Seeme	con	6.5	0.15	150	189	1800	244	163	2.0	1.28	9370+/-2340	0.016+/-0.004	6.0+/-1.50	0.082+/-0.021
Estonia	con	6.0	0.19	162	191	1439	236	92	1.3	0.66	9500+/-2375	0.018+/-0.005	5.85+/-1.46	0.076+/-0.019
Kulmsoo	con	7.1	0.13	162	174	2422	141	119	1.0	0.57	8820+/-2205	0.032+/-0.008	7.30+/-1.83	0.070+/-0.018

APPENDIX C

Farmer Participatory Trial Metadata

Figure C.1. Map locations of the five spelt and rye Farmer Participatory trial sites at Fenwick Stead, Cresswell, Tughall and Fallodon Estate farms (Magistrali, 2019). Orange markers indicate sites only in 2017; blue markers indicate sites only in 2018.

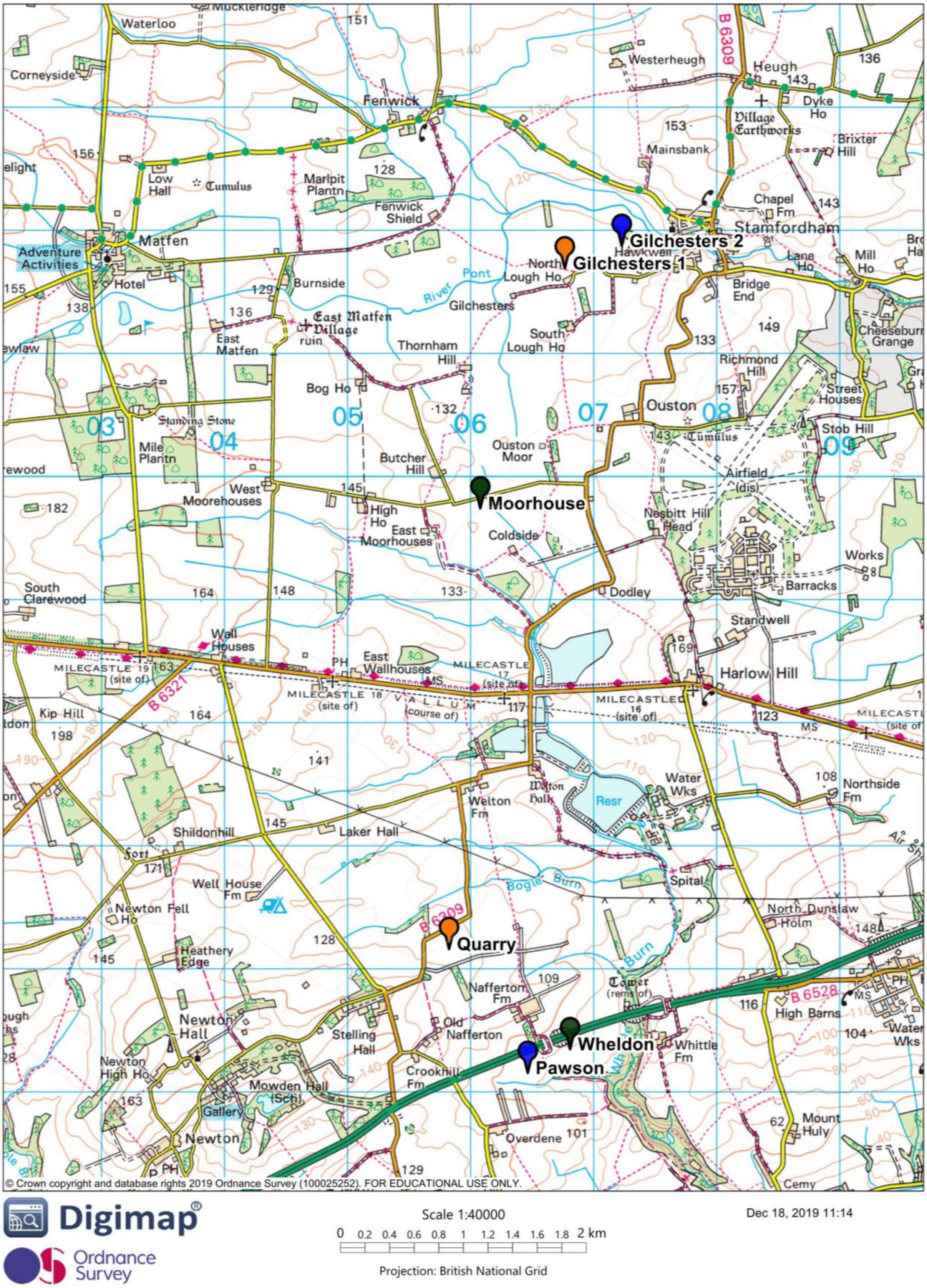

Figure C.2. Map locations of the six spelt and rye Farmer Participatory trial sites at Nafferton, Ouston and Gilchesters farms (Magistrali, 2019). Orange markers indicate sites only in 2017; blue markers indicate sites only in 2018; green markers indicate sites used in both trial years.

Figure C.3. Map locations of the spelt and rye Farmer Participatory trial sites at Gibside Community farm in 2017 (Magistrali, 2019).

Table C.1. Farm background information for all on-farm trial participants relating to basic location and farm type description.

Farm Name	Location	Coordinates	Elevation (m > sea level)	Size (ha)	Type	Management	Certification
Cresswell Farms	Belford	55.59285 -1.76278	32	880	Mixed	Organic	OF&G
Fallodon Estate	Alnwick	55.5176 -1.6737	80	570	Mixed	Organic	OF&G
Fenwick Stead	Belford	55.65005 -1.87354	30	283	Mixed	Non-Organic	None
Gibside Community Farm	Rowlands Gill	54.91025 -1.71626	170	5.2	Horticulture/ Arable	Non-Organic	Soil Association Conversion
Gilchesters Organic Farm	Hawkwell	55.03776 -1.90199	120	620	Mixed	Organic	OF&G
Nafferton (Conventional)	Stocksfield	54.98645 -1.8989	100	150	Mixed	Non-Organic	None
Nafferton (Organic)	Stocksfield	54.98645 -1.8989	100	150	Mixed	Organic	Soil Association
Ouston Farm	Stamfordham	55.02239 -1.90615	128		Arable	Non-Organic	None
Tughall Grange Farm	Chathill	55.53149 -1.66854	27	860	Mixed	Organic	Soil Association

Table C.2. Farm background information for all on-farm trial participants relating to typical management practices.

Farm Name	Livestock	Waste Process	Crop Rotation	Fertility	Pesticide	Weeding	Tillage
Cresswell Farms	100 suckler cows 1350 sheep	FYM	G/C, G/C, WW, SW, SBe, SO(u)	Cow/sheep manure	N/A	Cutting in grass	Plough, drill, roll
Fallodon Estate	250 beef cattle 700 sheep	FYM	G/C, G/C, G/C, WW, WW, SBe, SO	FYM and organic chicken manure	N/A	Hand-weed wild oats & ragwort	Plough & carrier
Fenwick Stead	300 beef cattle	Windrow composting	WW, OSR, WW, SBa, WW, SBa, G/S(u), G/S	NPK, FYM, Chicken Manure	PGRs, Herbicides, Fungicides	None	No-Till
Gibside Community Farm	None	GW composting	None	Compost	None	Hand-weeding	Plough
Gilchesters Organic Farm	67 beef cattle 1500 sheep	GW composting	WW, S/R, SBe, WW, G/C, G/C	FYM, GW compost, grazing, red clover	N/A	Einbock	Inversion plough, harrow/direct drill
Nafferton (Conventional)	150 dairy cows	Windrow compost, slurry	WW, WW, WB, OSR, WW, WB, G/C, G/C	FYM compost, slurry, NPK	Liberator	Einbock	Plough and press
Nafferton (Organic)	150 dairy cows	Windrow compost, slurry	WW, P, SB/SP, P, SBa, G/C, G/C, G/C	FYM compost, slurry	N/A	Einbock	Plough and press
Ouston Farm	None	None	WW, WW, WB, OSR, WW, WB, G/C, G/C	NPK	Liberator	Einbock	Plough and press
Tughall Grange Farm	1400 beef cattle 700 sheep	FYM composting	WW, SBa, SBe, G/C, SO(u)	FYM compost	N/A	None	Plough, cultivate, roll

Abbreviations: FYM—farmyard manure; GW—green waste; G/C—grass/clover, G/S—grass/silage OSR—oilseed rape; P—potatoes; SBa—spring barley; SBe—spring beans; SO—spring oats; SP—spring peas; S/R—spelt/rye; SW—spring wheat; WB—winter barley; WW—winter wheat; (u)—undersown.

Table C.3. Field information for each site where the Farmer Participatory spelt and rye trials were sown in both trial years (2016-2018).

Site	Farm	Soil	Slope (°)	Orientation	Size (ha)	Prior Crop	Surrounding Crop
			2017				
Gibside	Gibside	Clay loam	0	East-west	5.2	G/C	G/C
Gilchesters 1	Gilchesters	Heavy clay loam	1	East-west	5.6	WW	Spelt
Moorhouse	Ouston	Sandy loam	0	East-West	5.1	G/S	SBa
Newlands	Cresswell	Silty clay loam	0	North-south	13.6	WW	SW
Quarry	Nafferton C	Sandy loam	0	East-West	11.5	OSR	WW
Spindlestone	Cresswell	Silty clay loam	8	West	7.76	SW	SBe
Wheldon	Nafferton O	Sandy loam	5	East-West	17.5	G/C	SBa, G/C(u)
			2018				
Applebys Whin	Fallodon	Clay loam	2	North-south	19	SBe	WW
Gilchesters 2	Gilchesters	Clay loam	10	East -west	1.6	RC	WW
Moorhouse	Ouston	Sandy loam	0	East-west	5.1	SBa	WW
Pawson	Nafferton C	Sandy loam	5	East-west	7.8	WB	OSR
Three Cornered	Fenwick Stead	Medium clay loam	1	West	7	SBa	WW
Tughall	Tughall	Clay loam	0	North-south	4.49	WW	WC (wheat/beans)
Wheldon	Nafferton O	Sandy loam	5	East-west	17.5	SBa, GC(u)	G/C

Abbreviations: C—Conventional; O—Organic; G/C—grass/clover, G/S—grass/silage; OSR—oilseed rape; RC—red clover; SBa—spring barley; SBe—spring beans; SW—spring wheat; WB—winter barley; WC—wholecrop; WW—winter wheat; (u)—undersown

Table C.4. Fertility, weeding and tillage activities at each site during the 2016-2018 Farmer Participatory trial.

Site	Farm Fertility	Fert. Date	Biogas Digestate	Bio. Date	Weeding	Tillage
			2017			
Gibside	None	N/A	100kg N/ha	16 May	None	Plough, press, drill
Gilchesters 1	None	N/A	100kg N/ha	16 May	None	Plough, harrow, drill
Moorhouse	0.13kg/ha Muriate of Potash & 15.7kg/ha Triple Super Phosphate 420L/ha Omex 26%N 5%SO3	21 March 21 March 15 May	100kg N/ha	15 May	None	Plough, press, drill
Newlands	5t/ha cow manure	April	None	N/A	None	Carrier, drill
Quarry	100kg N/ha Mineral N	15 May	100kg N/ha	15 May	None	Plough, combination drill
Spindlestone	5t/ha cow manure	April	None	N/A	None	Carrier, drill
Wheldon	None	N/A	None	N/A	None	Plough, press, drill
			2018			
Applebys Whin	None	N/A	None	N/A	None	Plough
Gilchesters 2	None	N/A	100kg N/ha	8 May	None	Plough, harrow, drill
Moorhouse	100kg N/ha Mineral N	8 May	100kg N/ha	8 May	None	Plough, press, drill
Pawson	100kg N/ha Mineral N	8 May	100kg N/ha	8 May	None	Plough, press, drill
Three Cornered	163kg/ha Urea 120kg/ha Ammonium Sulphate	20 April 16 May	None	N/A	None	No-Till, direct drill
Tughall	None	N/A	None	N/A	None	Plough, harrow, rolled
Wheldon	None	N/A	None	N/A	Einbock	Plough, press, drill

Table C.5. Chemical crop protection activities at Farmer Participatory trial sites where synthetic herbicides, fungicides, pesticides and plant growth regulators were applied.

Site	Herbicide	Herb. Date	Fungicide	Fung. Date	Pesticide/PGR	Pest. Date
			2017			
Moorhouse	28g/ha Ally Max SX	18 May	0.35L/ha SiltraXpro	30 May	2L/ha Archer	30 May
	0.6L/ha UPL Minstrel	21 June	0.13L/ha SiltraXpro	21 June	0.53L/ha Archer	21 June
	1.5L/ha Monsanto Rodeo	17 August	0.5L/ha Sinconil	21 June		
	0.2L/ha Katalyst	17 August	0.05L/ha Bontima	21 June		
			0.03L/ha Adama Keystone	21 June		
			0.13L/ha BASF Tracker	21 June		
			2L/ha OPTE-MANG	21 June		
Quarry	1.5L/ha Isomec Ultra	18 April	2L/ha Bravo	10 May		
	0.35L/ha Cleancrop Gallifrey	18 April	2L/ha Bravo	22 May		
			2018			
Moorhouse	0.6L/ha Liberator	6 Nov 2017	2L/ha Bravo	15 May		
	1L/ha Cortez	15 May	2L/ha Bravo	24 May		
	1L/ha Cortez	24 May				
Pawson	0.6L/ha Liberator	6 Nov 2017	2L/ha Bravo	15 May		
	1L/ha Cortez	15 May	2L/ha Bravo	24 May		
	1L/ha Cortez	24 May				
Three Cornered	0.3L/ha Pincer	2 Nov 2017	1.35L/ha Alto Elite	27 April	0.1L/ha Moddus	27 April
	3L/ha Quidam	2 Nov 2017	1.25L/ha Treoris	13 May	0.2L/ha Moddus	13 May
	0.15L/ha Anchor	2 Nov 2017	0.6L/ha Rubric	13 May	1.25L/ha CCC 750	13 May
	25g/ha Monitor	7 May	0.5L/ha Bravo 500	13 May		
	0.5L/ha Intracrop Quorum	7 May	0.54L/ha Elatus Plus	1 June		
	0.72L/ha Cortez	1 June	1.09L/ha Ortiva Opti	1 June		
			1L/ha Adama Monkey	17 June		
			1L/ha Manzate 75 WG	17 June		

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