



## Review of the objectives of modern plant breeding and their relation to agricultural sustainability

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## Executive Summary

### Background

This project was commissioned by the British Society of Plant Breeders (BSPB) to provide an independent review of plant breeding activities and their contribution to sustainability in agriculture. UK and EU crop production needs to play its part in addressing the challenges of an increasing global population, climate change and a growing demand on resources such as land, water and nutrients. Plant breeding can play a vital role in helping the agricultural industry to help meet these challenges and, by doing so, help to secure food production for future generations by breeding crops with higher yields, resistance/tolerance to diseases, resistance/tolerance to pests, improved crop quality, reduced lodging and improved resource use efficiency. The only route to market for plant breeding R & D in the UK is through new varieties developed and commercialised by the private sector which is funded by its royalty income on seed production and sales. The extent to which the plant breeding industry is able to conduct more exploratory and strategic research to meet these challenges depends on companies' ability to access public funding through private/public funded collaborative research.

### Aims and Objectives

This project report provides an objective and transparent review of the objectives of modern plant breeding and assesses the extent to which these objectives are congruent with the definitions of sustainability in agriculture.

Specific objectives of the report are to:

- Review relevant evidence to determine the key themes and objectives of modern plant breeding;
- Determine the interpretation of sustainability in the context of plant breeding;
- Provide a discussion and gap analysis, determining the extent to which the objectives of modern plant breeding are commensurate with the interpretation of sustainability in agriculture.

### Methodology

This report is based on a desk exercise using existing evidence and information. The scope of the project was limited to the plant breeding objectives in wheat, barley, oats, oilseed rape, pulses, forage maize and herbage crops. The results presented are based on only published information and research that is available in the public domain and as such there may be research elsewhere showing greater achievements and progress than found in this report, although this is not included here.

The project involved assessing multiple sources of literature to determine the definition of sustainability in modern agriculture. Sources reviewed included Reaping the Benefits (Royal

Society, 2009), Foresight Report: Future of Food and Farming (Foresight Report 2011), Defra Green Food Project (Defra, 2012b), UK agricultural technologies strategy (Defra, 2013e) and the Common Agricultural Policy (CAP) (Europa, 2012). The objectives of plant breeding were then mapped to the definition of sustainable intensification given in the Foresight Report Future of Food and Farming (2011) under three main headings: *raising yields, improving resource use efficiency and reducing negative environmental impacts of food production*, with any gaps between the goals of sustainability and plant breeding objectives highlighted. A section on how plant breeding has influenced genetic diversity follows the discussion of how plant breeders have met the objectives of sustainable intensification.

## Results

### Definition of sustainability in modern agriculture

Our research looked at plant breeding in the context of the definition of sustainability in modern agriculture which relates to meeting the demands of increasing food production whilst minimising the impact of agriculture on the environment. Sustainable food production is necessary to meet the key challenges facing agricultural production including changing consumption patterns, increasing resource consumption, growing demand for livestock products, growing demand for biofuels, increasing water and land scarcity and mitigating against the adverse impacts of climate change. Sustainable food production requires that relatively little new land is brought into agricultural production; instead the land that is already in agricultural production needs to be used more intensively. Sustainable intensification is defined by the Foresight Report on the Future of Food and Farming as “...simultaneously raising yields, increasing the efficiency with which inputs are used, and reducing the negative environmental impacts of food production. It requires economic and social changes to recognise the multiple outputs required of land managers, farmers and other food producers and a redirection of research to address a more complex set of goals than just increasing yield”.

Achieving sustainable intensification requires action by policy makers, researchers and industry representatives. The role of plant breeders over the last ten years in helping the wider agricultural industry achieve sustainable intensification of agriculture is discussed, under the criteria of raising yields, improving resource use efficiency and reducing the negative environmental impacts of food production, with research activity targeted to sustainability goals found in the each of the public, public/private and private arenas.

### How has plant breeding met the objectives of sustainable intensification?

#### Raising yields

Plant breeders have aimed to improve and protect potential, harvestable and marketable yield via selecting for yield *per se*, targeting crop quality and selecting for resistance/tolerance to diseases and pests.

#### Yield improvements

Genetic improvement through plant breeding has led to an increase in wheat yields of 0.5t/ha/decade over the last 50 years and oilseed rape yields increasing by 0.5 t/ha/decade since 1980. Plant breeding has also led to large improvements in forage maize, herbage and sugar beet yields, with genetic factors being responsible for 0.109 t/ha/year increase in forage

maize yield (1977-2007) and 0.105 t/ha/year increase in sugar beet yield (1982-2007). Little evidence was found relating to yield improvement in field bean and pea yields over the last decade.

### Crop Quality

Protecting and enhancing marketable yield is linked to improved crop quality that meets market requirements. Milling and malting quality have been key selection criteria in wheat and barley crops, with associated improvements in efficiency of production. Plant breeding has also targeted improvement in oat digestibility via decreasing the fibre content of oats and selecting for increased oil content to promote use in non-ruminant diets. Plant breeders have also altered the fatty acid content of oilseed rape to meet market requirements and targeted a reduction in anti-nutritional factors present in oilseed rape to promote use in non-ruminant diets. In pulse crops, plant breeders have targeted a reduction in negative factors which affect digestibility or animal health via targeting genes *zt1* and *zt2* which reduce tannin levels and improving screening methods of vicine and convicine which are toxic glycosides that can have negative health effects. In herbage crops, forage quality has become an important driver of plant breeding with focus on improving dry matter content, energy content, starch content and digestibility to maximise livestock performance. In sugar beet, bolting resistance has been a breeding target with research focusing on developing a better understanding of the physiological processes controlling bolting and the potential link between gibberellic acid (GA) metabolism and bolting.

### Resistance to lodging

Resistance to lodging has been a driver of plant breeding as a means to protect harvestable yield across most crop groups. Recent research in this area has focused on identifying height genes which can allow high yielding wheat varieties of the optimal height to be produced and developing molecular markers for use in plant breeding programmes to exploit genetic variation in stem and anchorage strength between wheat cultivars. The QUOATS research programme, which is a five year research project (LK09124) which aims to develop and apply state-of-the-art genomic and metabolomic tools for oat genetic improvement is also focusing on using molecular markers to identify dwarf genes to aid selection for lodging resistant varieties in oats.

### Resistance/tolerance to diseases

Developing varieties that show resistance/tolerance to diseases has been shown by this review to be a major driver of plant breeding efforts across all crops, with winter wheat and barley in particular, having resistance to a wide range of diseases. There is also work underway to further the scope of disease resistance across all crop groups, for example quantitative trait loci (QTLs) have been identified for resistance to verticillium wilt in oilseed rape and work is underway to develop suitable varieties for UK markets with resistance to powdery mildew, *Ascochyta* blight and pea seed borne mosaic virus (PSbMV) in peas, fusarium in forage maize and Beet Mild Yellowing Virus (BMV) and Beet Yellowing Virus (BYV) in sugar beet.

### Resistance/tolerance to pests

Resistance/tolerance to pests has also received some breeding focus, particularly in wheat (orange wheat blossom midge, OWBM), oilseed rape (turnip yellows virus, TuYV) and sugar

beet (beet cyst nematode, BCN). This review suggests that there is scope for plant breeders to further improve resistance/tolerance to pests across all crops studied if resistance/tolerance to a specific pest is required by the market place. There is some work being carried out focusing on developing cereal varieties resistant to aphids that can cause Barley Yellow Dwarf Virus (BYDV), and there is scope for developing cabbage stem flea beetle (CSFB) resistance or targeting wider application of Turnip Yellow Virus (TuYV) resistance in UK oilseed rape varieties.

### **Increasing resource use efficiency**

Resource use efficiency in the context of plant breeding has focused on improving the efficiency with which the plant uses resources, principally water and nutrients. Resource use efficiency is linked to improving yield, where inputs remain the same, with higher yields resulting in more efficient use of nutrients and hence reduced emissions per tonne of output.

#### **Water use efficiency**

There has been some focus on improving water use efficiency (WUE) in wheat and herbage crops via projects such as EUROOT, the New Wheat Root Ideotypes LINK and LINK project LK0688 which aims to develop forage varieties that can maintain crop performance under limited soil water and nutrients.

#### **Nitrogen use efficiency**

Nitrogen use efficiency traits have also received some research focus. Our review suggests that the nitrogen use efficiency of barley, oilseed rape and sugar beet has increased over the last decade with higher output per unit of input observed, whilst the change in nitrogen use efficiency in wheat is more debatable. Some progress has been made to identify low N optima traits, with QTLs linked to nitrogen use efficiency found in wheat, barley, oats, oilseed rape and forage maize and breeding targets such as optimising late season rooting, plant height, heading date, thousand kernel weight and grain protein yield identified. Genes linked to nitrogen use efficiency have also been discovered.

#### **Phosphorous use efficiency**

There has been some research carried out focusing on improving phosphorous use efficiency in herbage crops via the LINK project LK0685 which aimed to develop perennial ryegrass and white clover varieties with higher intrinsic phosphorus use efficiencies (PUE) in terms of P acquisition, utilisation and retention than currently available varieties for entry into National and Recommended List trials.

### **Reducing the negative environmental impacts of food production**

Reducing the negative environmental effects of food production requires adapting to and mitigating against climate change, promoting soil health and maintaining or improving water quality. Plant breeders have a direct role in breeding crops that are adapted to varying environmental conditions and an indirect role in maintaining/improving soil health and water quality.

#### **Adaptation to environmental extremes**

Protecting yield and mitigating against climate change can be achieved via developing crops that can perform well under environmental extremes such as drought or hard frosts. Plant breeding companies have breeding programmes in diverse environments, and, by selecting

crops in those different environments, helps to provide materials that are adapted to a broad range of different environmental conditions for use in their breeding programmes. Drought tolerance has received some research focus in wheat, herbage crops and sugar beet, with traits linked to drought tolerance identified and research underway focusing on characterising rooting. Research has also been carried out in pulse crops focusing on frost tolerance, with traits and gene loci linked to frost tolerance identified. Little work has been carried out in the UK focusing specifically on waterlogging or salinity tolerance across all crop groups.

### Soil health

To improve resource use efficiency plant breeders have targeted improved rooting in wheat and herbage crops which can enhance soil structure. An example of work in this area is Defra Project IF0145 which focused on the role of genetic improvement with respect to 'environmental sustainability' traits in herbage crops and aimed to reduce soil erosion and improve soil stability by changing shoot and root architecture.

### Water quality

Plant breeders have had an indirect effect on water quality via breeding for traits such as disease, pest and weed resistance/tolerance and resource use efficiency which can help to reduce the amount of nutrient or plant protection products applied to crops, consequently reducing surface run-off into watercourses. A specific example of where plant breeders have helped to improve water quality is through LINK project LK0973 which focused on reducing effects of diffuse pollution from pig and poultry units by developing and evaluating low phytate wheat germplasm and LINK project LK0980 which aimed to reduce diffuse pollution of poultry operations via selecting wheat cultivars of high and consistent nutritional quality thereby reducing wastage.

### Maintaining and improving genetic diversity

Genetic diversity within crop species is vital to enable the objectives of sustainable intensification namely raising yield, improving resource use efficiency and reducing negative environmental impacts of food production. Plant breeders have taken steps to contribute to, and maintain the genetic diversity of crop species by maintaining collections of genetic sources such as the Germplasm Resource Unit, the Watkins Landrace Wheat Collection, The John Innes Pisum Collection, Gediflux collection and others. Plant breeders have also participated in research designed to maintain and improve the genetic diversity within crop species such as the Wheat Improvement Strategic Programme (2011-2017) and are also part of Defra funded initiatives to improve genetic diversity such as the Wheat Genetic Improvement Network (WGIN), Oilseed Rape Genetic Improvement Network (OREGIN) and Pulse Crop Genetic Improvement Network (PCGIN).

### Summary of impact of plant breeding for specified traits across crop groups

Figure 1 provides a summary of our research findings, such as highlighted above, and shows examples of the impact plant breeding has had on particular traits linked to aspects of raising yields, improving resource use efficiency and reducing the negative impact of food production. Blue coloured boxes denote where we found evidence of traits which have already had an impact in the market place due to the efforts of plant breeders, although ongoing work is

required in these areas to keep developing improved varieties that meet sustainability goals in the future and to address other specific issues. The green boxes relate to areas of plant breeding where we found that work is in the breeding pipeline or where little work has currently been carried out in this area.

Trait	Wheat	Barley	Oats	Oilseed rape	Field Beans	Field Peas	Forage Maize	Herbage	Sugar beet
Increase harvestable yield	Increase by 0.7t/ha decade since 1980	92% increase in W.B & 87% in S.B since 1982	Improve harvest index and no. grain per sq. metre	0.5t/ha increase per decade since 1980	Little increase seen in last 10 years	Little increase seen in last 10 years	Focus on DM and starch yield	Focus on DM yield	Faster increase than any UK arable crop since 1980
End use quality	Bread making quality	Low $\beta$ -glucan levels, low $\beta$ -amylase	Naked oats, oil content	Decrease glucosinolate & fibre	Reduce tannins, amino acid content		Digestibility, energy content	Sugar content	
Resistance to disease	Eyespot Sept., rust	Mildew, rust, Rhyncho. Ramularia, Net blotch	Rust, mildew	LLS, stem canker	Leaf and pod spot	Pea wilt, Downy mildew	Eyespot	Mildew, Rhyncho. rust	AYPR
				Verticillium, alternaria	Ascochyta blight, rust	P. mildew, Ascochyta	Fusarium		BMYV, BYV
Resistance to pests	OWBM	Little work	Little work	TuYV	Stem nematode resistance	Little work carried out	Corn borer resistance	Little work	BCN tolerance
	Aphid, BYDV								
Adaption to env. extremes	Drought traits identified	Little work	Little work	Little work	Traits identified	Traits identified	QTLs found	Drought tolerant	Traits identified

Impact in market place

Work in progress/development required

**Figure 1. Examples of the impact plant breeding has had on specified traits in major arable crops**

### Conclusion

Plant breeding has been a major contributor to meeting the goals of sustainability and provides an important basis for multiple objectives of sustainability to be met. Our research suggests that the main emphasis of commercial plant breeding in the last ten years has focused on enhancing and protecting yield in major arable crops, thereby driving greater production from the same amount of land, a key requirement of sustainable intensification. Crop quality and resistance/tolerance to diseases and pests are linked to this and have resulted in varieties being available in the market place. Yield focus also delivers benefits to resource use efficiency and the environment by improving nutrient and water use efficiency through higher yields being attained with the same level of input, hence resulting in lower emissions per tonne of output. Further work is in progress, or required, by plant breeders to develop commercial varieties which deliver further improved nutrient and water use efficiency, photosynthetic efficiency and climate resilience. To enable varieties with these traits to be available in the market place both public and private/public funding partnerships are important to build on the real strengths that have been identified in delivering traits that are already available on the market. These partnerships can also fill in the research gaps where

there has been a lack of evidence of investment and activity, such as resistance/tolerance to pests in barley.

## 1 Introduction

Climate change, lack of resources and increased demand on resources such as land, water and nutrients are key issues facing global agriculture. To tackle these issues, agricultural production must be sustainable, which encompasses producing safe and healthy food, conserving natural resources, delivering ecosystem services and ensuring economic viability (European Commission, 2012). Plant breeding underpins successful crop production and involves the science of adapting the genetics of plants to improve yield, in field performance and end use quality. The development and commercialisation of agricultural plant varieties that meet the demands of sustainable agricultural production is dependent on the ability of plant breeders to carry out research and development activities. Plant breeding relies heavily on private funding, and has done since the Barnes review of Government funding for near market research in the 1970s where the decision was taken to cease public funding of plant breeding. Some public funding remains, for example, for oats, grass and clover at IBERS and for potatoes and barley at the James Hutton Institute, but otherwise plant breeding and the delivery of new varieties to the market is reliant on funding from the private sector through royalty income from seed production and sales. This level of funding can limit the ability of plant breeders to fund the more exploratory pre-breeding and strategic research needed to enable plant breeders to make step changes in innovation. As such, public/private partnerships and public funding are vital for underpinning strategic research in plant breeding, particularly in crops that are less significant in economic terms, but strategically important for the UK such as field beans where the financial viability of breeding has been on a knife edge for some time and public sector investment in collaborative research is fundamentally important.

In this report we compare the definition of sustainable intensification in modern agriculture with the objectives of modern plant breeding, highlighting where sustainability and plant breeding objectives are commensurate and where improvements can be made, with evidence coming from each of the public, public/private and private arenas.

## 2 Aim and Objectives

### 2.1 Project aim

The aim of the project is to provide an impartial and transparent review of the objectives of modern plant breeding to assess the extent to which these objectives are congruent with the definitions of sustainability in agriculture.

### 2.2 Objectives

The overall objective of the work is to assess the extent to which the objectives of modern plant breeding are commensurate with the goals of sustainability.

Specific objectives are to:

- Review relevant evidence to determine the key themes and objectives of modern plant breeding;

- Determine the interpretation of sustainability in agriculture;
- Provide a discussion and gap analysis, determining the extent to which the objectives of modern plant breeding are commensurate with the interpretation of sustainability in agriculture.

### 3 Methodology

#### 3.1 Defining sustainability in modern agriculture

To determine the definition of sustainability in modern agriculture, a focused literature review of key documents related to sustainability and sustainable intensification, was carried out.

Sources reviewed included:

- Reaping the Benefits (Royal Society, 2009);
- Foresight report -The Future of Food and Farming (Foresight Report, 2011);
- Defra Green Food Project (Defra 2012b);
- UK strategies for agricultural technology (Defra, 2013e);
- Definitions of sustainability under the Common Agricultural Policy (Europa, 2012).

#### 3.2 Defining objectives of modern plant breeding

A literature review was carried out to determine main themes of modern plant breeding in the UK and EU. The scope of literature review was limited to the plant breeding objectives in wheat, barley, oats, oilseed rape, pulses, forage maize and herbage. Literature was gathered from scientific, readily available and grey sources, including Scopus. Science Direct, CORDIS (Europa) which is the European Commission's primary public repository and portal to disseminate information on all EU-funded research projects, Defra Science Search and levy boards, such as AHDB/HGCA, publications.

To collect relevant scientific abstracts from Scopus the principles of a systematic review were followed to ensure objectivity which involved: 1) developing a search question (Figure 1), 2) gathering literature from multiple sources, 3) screening literature for inclusion in the report and 4) reviewing literature.

**Search question:** What evidence is available from peer reviewed scientific literature, readily available literature and grey literature that defines the key themes and objectives in plant breeding over the last 10 years?

**Figure 1. Search question developed to assess the objectives of modern plant breeding**

To undertake the Scopus literature search, search criteria were developed and then searched for in the Scopus database.

Below is an example of the type of structured search string which was used to search academic and peer reviewed literature in Scopus:

TITLE-ABS-

KEY ( **barley** AND **variety** OR **breeding** AND **objectives** OR **aims** AND **eu** OR **europe** ) AND PUBYEAR > 2003

### 3.2.1 Selection Criteria

Scientific abstracts found from Scopus were reviewed before inclusion in the literature review based on their title and abstract only. Selection criteria were applied as shown in Table 1 to ensure that all the papers that were included in the review were relevant. The scientific papers that passed the selection criteria and were relevant to include in the report were found in Science Direct and analysed along with outputs from other ready available, published or grey literature. Once data were extracted from these sources, key themes were drawn out and have been summarised in the following report.

**Table 1 Selection criteria for Literature Review**

Screening Questions	Inclusion Values
Study refers to the objectives or aims of plant breeding industry/variety selection/cultivar selection	Yes
Study refers to value for cultivation and use?	Yes
Abstract in English	Yes
Study refers to benefits of plant breeding	Yes
Study refers to weaknesses or improvements needed in plant breeding	Yes
Study relates to the effects of plant breeding <i>e.g., disease resistance, crop safety, lodging resistance, pest resistance</i>	Yes

### **3.2.2 Comparison of definition of sustainable intensification with the objectives of modern plant breeding**

Then objectives of modern plant breeding were mapped to the three elements of sustainable intensification specified in the Foresight Report; *raising yields, resource use efficiency and reducing the negative environmental impact of food production*. Any gaps between plant breeding objectives and the definition of sustainability were highlighted.

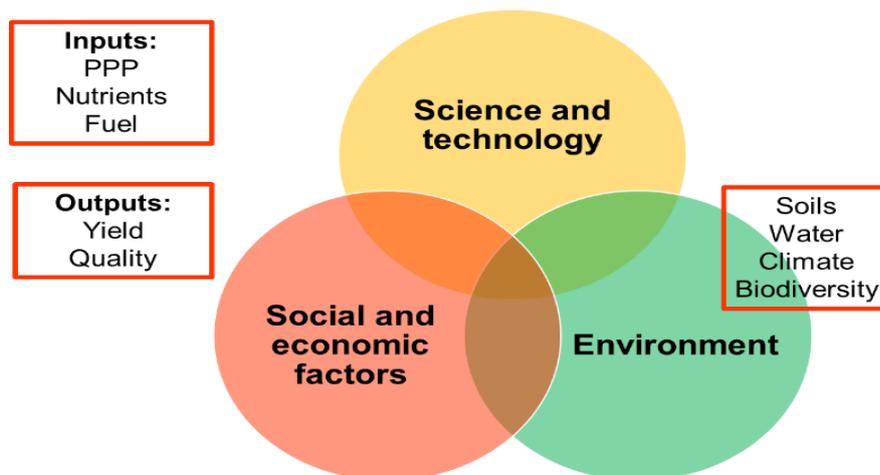
A brief discussion of the role of plant breeders in maintaining and improving genetic diversity follows the discussion of how plant breeders have met the objectives of sustainable intensification.

## **4 Results and Discussion**

### **4.1 Definition of sustainability in modern agriculture**

Sustainability in modern agriculture involves meeting the demands of increasing food production whilst minimising the impact of agriculture on the environment. Sustainable food production is necessary to meet the key challenges facing agricultural production including changing consumption patterns, increasing resource consumption, growing demand for livestock products, growing demand for biofuels, increasing water and land scarcity and mitigating against the adverse impacts of climate change (Royal Society, 2009).

The rising global population is predicted to put increased demands on the food production system. So far, increases in agricultural production have been made via increasing yields rather than bringing much new land into agricultural production (Foresight Report, 2011). This trend must continue for food production to be sustainable (Royal Society, 2009; Foresight Report, 2011), with the land that is already in agricultural production being used more intensively. Simply producing enough food to feed the growing population, i.e. achieving food security, is not a viable answer to the challenges posed by an increasing population; the social, economic and environmental aspects of food production must also be taken into account (Royal Society, 2009, Figure 2).



**Figure 2. Elements of sustainable food production with key inputs and outputs shown**

*Source: Royal Society (2009).*

#### **4.1.1 Social factors of sustainability**

Social factors of sustainability include the access to, and availability of, food, the impacts of food production on health status and the reliance on food production for income (Foresight Report, 2011). Improvements in wealth due to increases in food production are expected to lead to a major dietary shift within the global population, with the amount of meat consumed globally expected to increase and the amount of traditional cereals, fruit and vegetables consumed predicted to decrease. This change is likely to have both social and environmental impacts by increasing demands on land grown for grain which needs to be balanced with land used for human food production and by increasing greenhouse gas (GHG) emissions via increased global livestock numbers (Royal Society, 2009).

#### **4.1.2 Economic factors of sustainability**

Food production influences the economic factors of sustainability; the global nature of the commodity market means that small changes in production can lead to large changes in commodity prices which can affect the viability of food production. Other external factors such as transport costs of commodities and uncertainties about market conditions can limit economic investment in global food production and as such, sustainable food production requires resilience within the supply chain to adapt to fluctuations in market prices (Royal Society, 2009; Foresight Report, 2011).

#### **4.1.3 Environmental factors of sustainability**

The natural environment is a key element of sustainable food production and provides valuable ecosystem services which benefit crop production such as soils, water and biodiversity needed for resilience to abiotic and biotic stressors and crop pollination (Royal Society, 2009). However, environmental conditions can also limit agricultural production through disease, pest and weed interactions with crops. The challenge for sustainable agriculture is to maximise food production across all land types, minimise resource use and use integrated control methods, including improved crop varieties to overcome the threat of diseases, pests and weeds.

#### 4.1.4 Sustainable Intensification

Sustainable intensification of modern agriculture is needed to meet the challenges facing global food production as this encompasses both food security goals and the economic, social and environmental factors that underpin food production. The definition of sustainable intensification is given by the Foresight Report on the Future of Food and Farming as *'...simultaneously raising yields, increasing the efficiency with which inputs are used, and reducing the negative environmental impacts of food production. It requires economic and social changes to recognise the multiple outputs required of land managers, farmers and other food producers and a redirection of research to address a more complex set of goals than just increasing yield'*. The definition of sustainable food production given by the Royal Society (2009) encompasses similar themes, suggesting that sustainable intensification of global agriculture is where yields are increased without adverse environmental impact and without the cultivation of more land, whilst the Agri-Tech Strategy (Defra, 2013e) refers to sustainable intensification as producing *'more with less'*.

Our evidence of the role of plant breeders over the last ten years in the UK and EU in meeting the objectives of sustainable intensification of agriculture across crop groups is discussed below, under the three criteria of sustainable intensification given by the Foresight Report Future of Food and Farming (2011): *raising yields, improving resource use efficiency and reducing the negative environmental impacts of food production*.

### 4.2 How has plant breeding met the objectives of sustainable intensification?

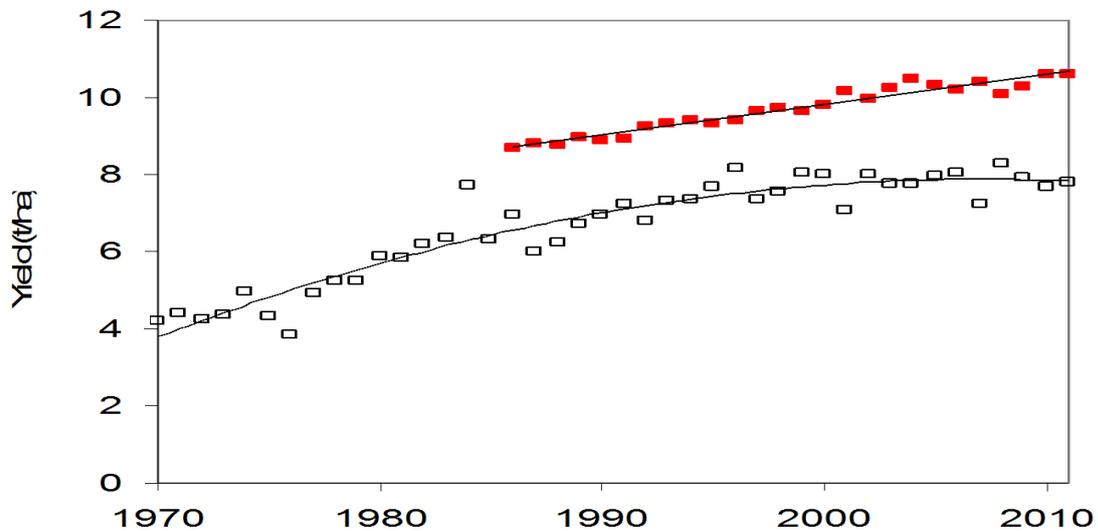
#### 4.2.1 Raising yields

The contribution of plant breeding to raising yields in each crop group is shown below. Overall, our review has found that across all crop groups studied plant breeders have focused on enhancing and protecting crop yields through improvements in crop physiology, improvements to crop quality and resistance and/or tolerance to diseases, pests and weeds; thereby contributing to one of the objectives of sustainable intensification.

## Enhancing yield

### Wheat

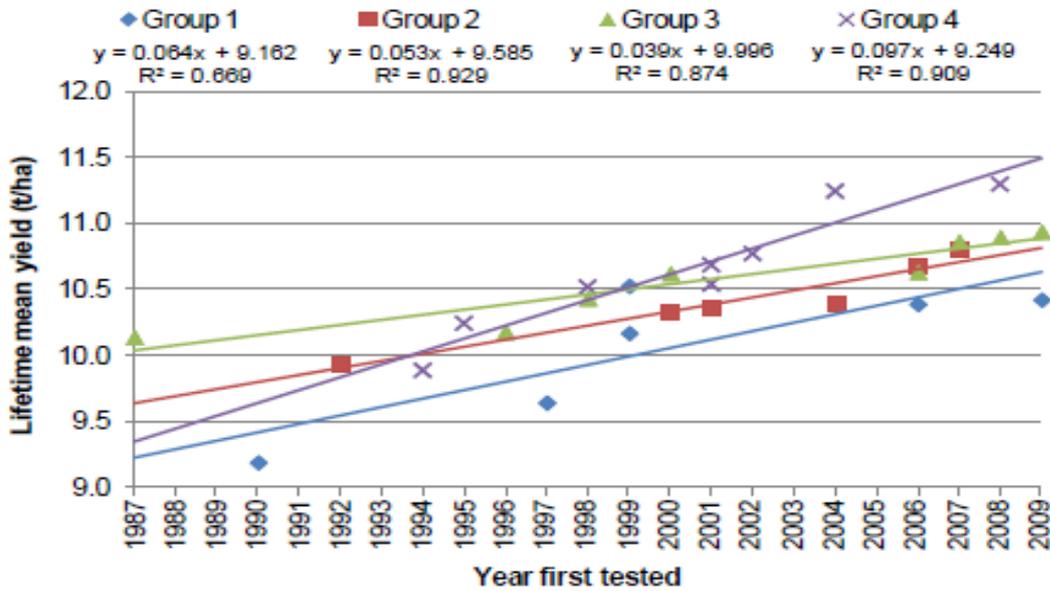
Increasing grain yield is the primary target of wheat breeding, with research showing that since 1982 at least 88% of the improvement in cereal yield can be attributed to genetic improvement (Mackay *et al.*, 2010), with findings from Germany highlighting that yield progress can be attributed to genetic improvement over the last 30 years, with agronomic factors of minor importance in overall yield progress (Laidig *et al.*, 2014). An analysis of AHDB Recommended List trials, which are a system of testing varieties to assess whether varieties have a balance of features likely to give an economic benefit to the industry, found that wheat yields have improved by 0.07 t/ha/year between 1997-2006 (Spink *et al.*, 2009) and by 0.05 t/ha/year over the last 50 years (Berry *et al.*, 2012; Figure 3).



**Figure 3. Yields from RL trials vs farm yields between 1970-2010**

Source Berry *et al.*, (2012)

Other research suggests that yields of wheat varieties in Groups 1, 2 (varieties suitable for bread making) and group 3 (suitable for biscuit making or distilling) have risen by about 0.04-0.06 t/ha per year, with Group 4 (suitable for feed) varieties increasing by 0.10t/ha/year (Knight *et al.*, 2012) (Figure 4). The increase in wheat yield is not confined to the UK; in Finland, plant breeders have improved the genetic potential of winter wheat yields by 0.046 t/ha/year and spring wheat yields by 0.004 t/ha/year between 1995-2005 (Peltonen-Sainio *et al.*, 2009).



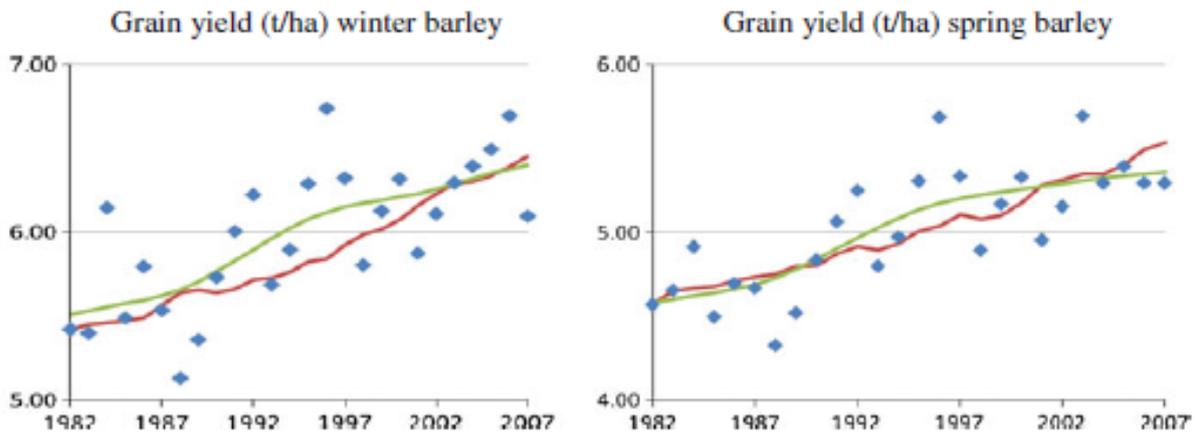
**Figure 4. Genetic yield improvement within winter wheat nabim Groups (x = 1 for 1987).**

Source: Knight *et al.*, (2012)

Traits linked to increased yield have been found and include early canopy closure, earlier stem extension, delayed canopy senescence, improved nutrient capture and conversion, improved light conversion, increased partitioning of dry matter into grain, increased water capture and conversion (Spink *et al.*, 2009), increased number of grains per m<sup>2</sup> (Peltonen-Sainio *et al.*, 2007), increased ears per m<sup>2</sup> and a faster crop growth rate pre-flowering (Clarke *et al.*, 2012).

### Barley

Plant breeding has increased barley yields; analysis of UK variety trials by Mackay *et al.*, (2010) shows that the contribution of genetics to barley yield was 86% from 1948 to 1981 and 110% from 1982 to 2007 (Figure 5).



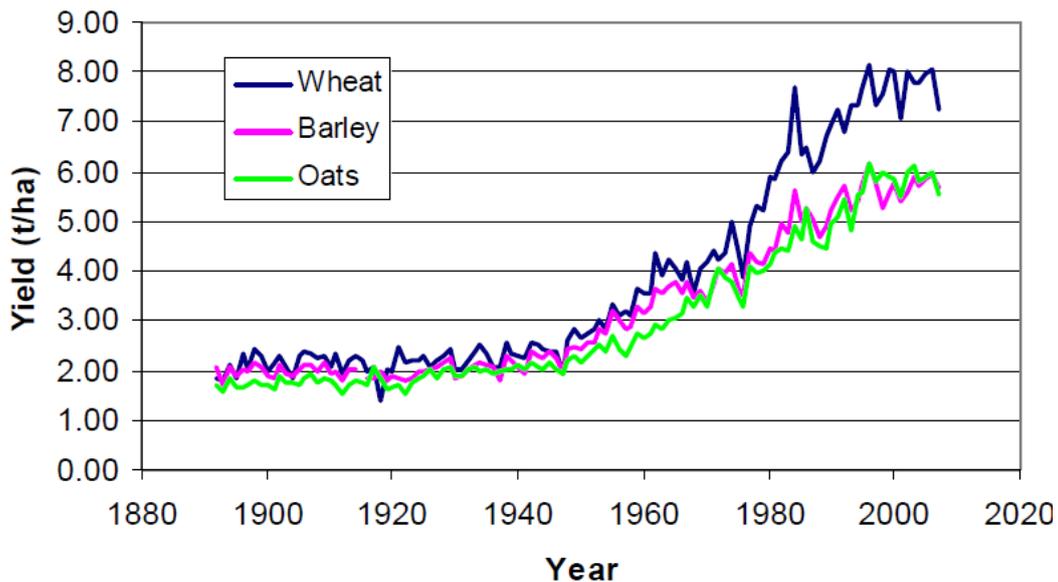
**Figure 5. Estimated contribution of variety improvement to national yield increases (t/ha) 1982-2007. Blue diamonds- national yield, green line (3df)- spline fitted to national yield, red line- contribution of the variety effect to national yield.**

Source: Mackay *et al.*, (2010)

In Norway it has been estimated that 48% of the yield improvements seen in barley between 1946–2008 was due to the introduction of new barley varieties and this effect was greatest between 1980-2008, compared to other periods (1946–1960 and 1960–1980) (Lillemo *et al.*, 2010). Similar findings come from Bingham *et al.*, (2012) who found a positive relationship ( $P < 0.001$ ) between spring barley yield and the year of variety introduction indicating a significant improvement in yield with breeding over time. Similarly to wheat, traits linked to increased yield have been found (Bingham *et al.*, 2012; Mansour *et al.*, 2014).

### Oats

UK oat yields have increased over the last 20 years from around 4.0t/ha in 1980's to around 5.5t/ha in 2007 (Spink *et al.*, 2009, Figure 6), whilst in Finland, plant breeding has increased the genetic potential of oats by 0.03t/ha/year between 1995-2005 (Peltonen-Sainio *et al.*, 2009).



**Figure 6. UK cereal yields and Defra production statistics for wheat, barley and oats**

Source: Spink *et al.*, (2009)

Research has been undertaken to improve oat yields through the QUOATS project, which is a five year research project (LK09124) which aims to develop and apply state-of-the-art genomic and metabolomic tools for oat genetic improvement with molecular markers for height and yield identified (Marshall *et al.*, 2010). Current research specifically focusing on increasing oat yield is underway as part of the Biotechnology and Biological Sciences Research Council (BBSRC) funded project titled: 'Developing enhanced breeding methodologies for oats for human health and nutrition' (DEMON) which aims to improve key traits that will increase UK oat production (HGCA 2014a).

### Oilseed rape

Plant breeders have successfully increased oilseed rape yields in AHDB Recommended List (RL) trials by 0.5 t/ha per decade since 1980 (Spink and Berry, 2005), with research from Knight *et al.*, (2012) concurring. These yield improvements have been made via selecting for improved plant survival over winter, increased germination percentage (Rathke *et al.*, 2006), increased seed weight per pod, increased pod length, increased seed number m<sup>2</sup> and increased branch density (Morgan *et al.*, 2010).

### Field beans

Research suggests that there has been little improvement in field bean yields over the last ten years due to lack of research investment and the difficulty of breeding for increased yield which has meant only a limited number of varieties have entered the AHDB Recommended List system each year (Weightman, 2005). However, sufficient genetic diversity exists within current cultivars to target traits such as increased number of branches/plant, straw yield/plant and pods/plant (Peksen and Artik, 2009) that are linked to higher yields (Weightman, 2005). There are also a number of EU and UK initiatives underway to address low yield in pulse crops; e.g. the EU-funded project ABSTRESS which aims to develop legume crops with improved resistance to biotic and abiotic stressors which can help to protect yield as well as the industry/academic collaboration PROTYIELD which aims to eliminate the negative trade-off between yield and protein content. In the UK, Defra has also funded The Pulse Crop Genetic Improvement Network (PCGIN) which aims to exploit the sources of genetic diversity maintained at UK-based institutes such as the John Innes Centre and NIAB to improve pulse crop quality and performance. Improved yield stability in field beans is also a focus of the Optibean project, led by independent UK breeder Wherry & Sons and funded by Innovate UK

### Field peas

Plant breeders have increased field pea yields in Recommended List trials by 0.05 t/ha/year between 1993-2002 (Weightman, 2005). No evidence was found of continued yield increases since 2002. Traits linked to increased yield have been found (Annicchiarico and Filippi, 2007; Weightman, 2005).

### Herbage

Most breeding efforts in herbage crops have focused on increasing yield in perennial ryegrasses as this species represents around 50% of the marketed grass seed in Europe (Humphreys *et al.*, 2010). Genetic improvements in diploid perennial ryegrass cultivars registered on European National Lists has increased total dry matter yield by +3.2% per decade, increasing by 2.8% per decade in summer and 7.4% per decade in the autumn over the last 40 years (Sampoux *et al.*,

2011). Ploidy, which is the number of sets of chromosomes in the nucleus of a cell, also has an effect on yield, with Burns *et al.*, (2013) showing that tetraploid perennial ryegrass varieties can show a dry matter (DM) yield advantage of 0.66 t/per annum in field trials over diploid varieties. Research has also shown it is possible to select for root dry matter and high yield in perennial ryegrass (Deru *et al.*, 2014). Traits linked to increased yields in herbage crops have been identified and include increasing leaf:stem ratios (Annicchiarico, 2007), plant height, increasing number of internodes (Tucak *et al.*, 2013) and increasing earliness (Sampoux *et al.*, 2011).

Breeding objectives in white clover (*Trifolium repens L.*) focus on optimising the contribution of white clover to the sward rather than yield *per se*, as inclusion of white clover in the sward has additional benefits other than yield including nitrogen fixation, high protein content, digestibility, mineral content and high intake. The main breeding objectives in red clover (*T. pratense L.*) have been to target yield persistency and resistance to diseases and pests, although less research and genetic improvement has been carried out in this species compared to white clover (Abberton and Marshall, 2005).

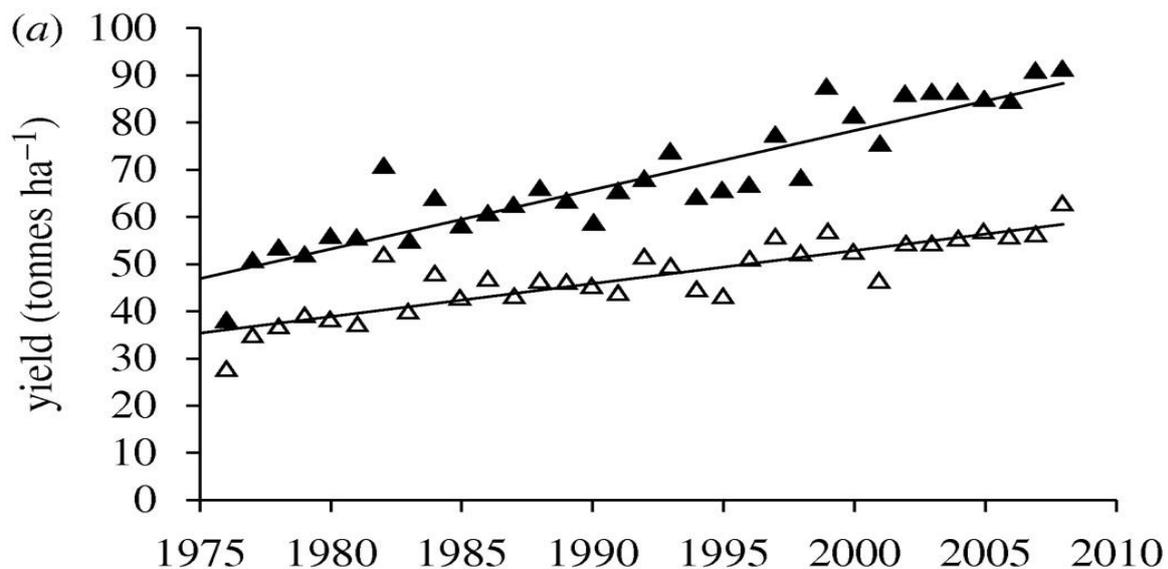
### Forage Maize

Analysis of UK variety trials by Mackay *et al.*, (2010) found that forage maize showed the most dramatic increase in yield of all crops analysed, with genetic and environmental sources of equal importance to the increase in yield, and genetic factors being responsible for 0.109 t/ha/year increase between 1977-2007. In recent years breeding progress has been made in reducing the trade-off between early maturity and yield (Abberton *et al.*, 2011). Modern breeding technologies have been used to improve forage maize yields such as use of full-sib reciprocal recurrent selection (RRS) and double haploids (Bordes *et al.*, 2006; Gallais and Bordes, 2007; Ordas *et al.*, 2012; Pena-Asin *et al.*, 2013).

### Sugar beet

In sugar beet, breeding has increased white sugar yields by 0.6–0.9% a<sup>-1</sup> from 1964 to 2003 via improved biomass partitioning, decreased concentration of K, Na, and amino N combined as standard molasses loss and enhanced assimilation (Loel *et al.*, 2014). This increase in sugar beet yields has also been seen in Europe, with Polish sugar beet yields increasing by 60% over the last 15 years (Jaggard *et al.*, 2010). Analysis of UK sugar beet yields in variety trials between 1982-2007 shows that the rate of genetic improvement in sugar beet was 0.105 t/ha/year, although overall environmental changes had more impact on yield than genetic improvement (Mackay *et al.*, 2010). Other UK research suggests that since the 1970's sugar beet yields in official variety trials have increased at an average annual rate of 0.204 t/ha (Jaggard *et al.*, 2007).

Despite yields from official variety trials increasing, farm yields have not followed the same trend (Figure 7). The British Beet Research Organisation (BBRO) has aimed to tackle this shortfall by introducing its 4x4 yield initiative to encourage growers to target a 4% yield improvement in their crops per year between 2012-2015.



**Figure 7. Sugar beet yield in official variety tests in the UK and national average yields in the same year. Open triangles-commercial yields, closed triangles variety trial.**

Source: Jaggard *et al.*, (2010).

## Crop Quality

### Wheat

Protecting and enhancing marketable yield is linked to improving crop quality. A key breeding objective in the UK and Europe is to produce high quality wheat for baking (Tohver *et al.*, 2007; Defra, 2009a). The main factors that affect wheat quality include moisture content, protein content, Hagberg Falling Number (HFN) and specific weight (HGCA Crop Committee Handbook, 2013). Other factors that affect wheat quality include hardness, vitreosity, grain N, gluten content and resistance to sprouting (Tohver *et al.*, 2007). Plant breeders have selected four different groups of wheat varieties that meet different quality criteria, for example Group 1 and 2 varieties have a minimum specification of 75 kg/hl specific weight and a Hagberg Falling Number of 230 seconds, whilst Group 4 feed wheats have lower specific weight targets requirements of 74 kg/hl and lower Hagberg Falling Number requirements of 150 seconds (HGCA Crop Committee Handbook, 2013).

Improving crop quality is an ongoing breeding objective; with plant breeding companies being part of the Crop Improvement Research Club (CIRC) which is a 5-year partnership between Biotechnology and Biological Sciences Research Council (BBSRC), The Scottish Government and others which aims to support research into quality and yield traits in wheat, barley and oilseed rape. Specific objectives of the CIRC are to develop better understanding of protein quality and functionality in wheat, non-starch polysaccharide functionality in wheat and barley and starch functionality in wheat and barley (BBSRC, undated).

### Consistency in Hagberg Falling Number (HFN)

Our review suggests that consistency in Hagberg Falling Number (HFN) values under a range of climatic conditions is a key breeding objective (Defra, 2009a). The two principal causes of low HFN are pre-harvest sprouting (PHS) and pre-maturity amylase (PMA) and the aim for plant

breeders is decrease PHS and PMA, thereby increasing HFN. PHS relates to the loss of dormancy resulting in premature germination of the grain whilst still on the parent plant (HGCA, 2010). Quantitative Trait Loci (QTLs) linked to PHS resistance have been identified, with no yield penalty associated with having PHS resistance. Three out of four PHS resistance QTL regions identified had an effect on grain size and QTLs also showed variable effects on height depending on the QTL in question which requires further investigation (Uauy *et al.*, 2013). PMA is caused by cold temperature shock in absence of visible germination, possibly due to increased sensitivity to gibberellic acid (GA) (Kondhare *et al.*, 2013) which can be addressed via identifying QTL linked to GA hypo-sensitivity and using these to develop breeding strategies to improve HFN stability.

### **Glutenin composition**

Breadmaking qualities are dependent on the number and composition of high molecular weight (HMW) glutenin subunits. The link between glutenin subunit composition and baking quality can be used by plant breeders as a selection criteria in breeding programmes. Cultivars with subunits 2+12 at the Glu-D1 locus and the cultivars with subunits 7+8 at the Glu-B1 locus have been shown to have higher values of Gluten Index and resistance to extensibility ratio (R/Ext) than other cultivars (Horvat *et al.*, 2008) which is linked to better baking quality. Baking quality has also been shown to be positively influenced by HMW glutenin subunits 1, 2, 7 + 9, 14 + 15, 17 + 18, 5 + 10 in German cultivars (Tohver *et al.*, 2007). Elimination of all  $\omega$ -gliadins, a soluble type of gluten, may also further improve wheat bread making quality (Waga and Skoczowski, 2014).

### **Relationship between protein content and yield**

To be eligible for the entry onto the AHDB Recommended List, milling wheat varieties must have a protein content of 12.2% or above (Crop Committee Handbook, 2013). However, selecting for higher grain yield tends to select for cultivars with lower protein content (Peltonen- Sainio *et al.*, 2012). Analysis of long-term datasets for spring cereals produced by MTT Agrifood Research Finland for 1970–2009 and Boreal Plant Breeding Ltd. for 1991–2009 showed that there are cereal lines that can combine relatively high yields with high protein concentrations and which do not exhibit any disadvantageous characteristics, highlighting that plant breeding material exists to target both high yield and high protein in wheat (Peltonen- Sainio *et al.*, 2012), with other research suggesting that improving protein stability in modern wheat varieties should be a key breeding target (Dvořáček *et al.*, 2014).

### **Barley**

To be accepted by maltsters, barley varieties have to meet defined quality criteria. Hot water extract, kernel size fractions, kernel weight,  $\beta$ -glucan, malting losses, friability,  $\alpha$ -amylase activity, viscosity and soluble nitrogen ratio (SNR) are common criteria used to test the quality of breeding lines, with specific weight and nitrogen content key quality criteria (Gupta *et al.*, 2010). Amylases play an essential role in malting by facilitating starch breakdown, with the thermostability of  $\beta$ -amylase an important trait required in malting production. Plant breeders have recognised this, and have decreased the occurrence of the  $\beta$ -amylase allele with the lowest thermostability (Bmy1-Sd2L) in European barley varieties over the last 60 years (Chiapparino *et al.*, 2006), thus increasing efficiency of malting production.

Breeders have also bred for low  $\beta$  glucan levels in malting barley which improves processing efficiency. By doing so, breeders have created an extra 17.8 - 66.8 million potential bottles for

distillers with a retail value on the whisky export market of £129 - £483 million per annum and potentially an additional £148 million per annum worth of beer for brewers (DTZ, 2010). Another objective of plant breeders is to breed naked barley varieties which will improve processing efficiency, with some naked Himalayan varieties, and progeny from Himalayan x UK crosses, combining improved processing efficiency and seedling vigour, although further work needs to be done to breed naked barley varieties suitable for UK cultivation (Dickin *et al.*, 2010). In addition, the UK distilling market seeks non glycosidic nitrile (GN) barley varieties, as a breakdown product of glycosidic nitrile can produce traces of ethyl carbamate. In response, plant breeders have developed malting barley varieties with no GN levels such as Concerto and Odyssey.

## Oats

Crop quality has also been a breeding goal in oats, with breeding targeted towards ensuring grain has low screenings, a high kernel content, is easily de-hulled and free of discolouration (Marshall *et al.*, 2013). Improving the nutritional quality of oats has also been an objective of plant breeders, with research focusing on selecting for traits which can have human health benefits or that can reduce the anti-nutritional factors (ANF) present in oats.

### Human health benefits

Oats naturally have high levels of  $\beta$ -glucan which has been linked to numerous health benefits including lowering cholesterol (Andersson and Borjesdotter, 2011), with a QTL which accounts for 31% of the inheritance of  $\beta$ -glucan found on chromosome 7HL (Steele *et al.*, 2011). There has also been some interest from plant breeders in selecting oat varieties with high levels of ferulic and coumaric acid which are thought to have antioxidant properties (Kovacova and Malinova, 2007). Research has also focused on identifying polymorphisms in gluten-like avenins within oats which can cause negative reactions in some patients with coeliac disease (Mujico *et al.*, 2011). Breeding efforts in Finland have also aimed to gain a better understanding genetic control of Cadmium uptake in oat crops, as Cadmium (Cd) can be highly toxic to living cells at very low concentrations, with a QTL linked to low Cd accumulation identified (Tanhuanpaa *et al.*, 2007).

### Reduction of anti-nutritional factors (ANF)

Use of oats in non-ruminant diets has been limited due to the high fibre and low available energy content of current oat varieties. Breeders have responded to this by developing naked or huskless oats which are high in energy, with the QUOATS project currently focusing on breeding oats with a low-lignin husk to increase digestibility. Improving the oil content of oats for use in non-ruminant diets has also been an objective of plant breeders (Defra, 2004c; Marshall *et al.*, 2010; Wade and Maunsell, 2004) as increasing oil content can increase the metabolisable energy of naked oats (QUOATS, undated) with QTLs associated with protein and oil content in oats have been found (Tanhuanpaa *et al.*, 2010).

## Oilseed rape

In oilseed rape, there is some research underway for quality traits, however, uncertainty on nutritional and industrial demand does restrict progress in this area (Vincourt, 2014). Plant breeders have altered the fatty acid content of oilseed rape to suit different end user requirements and have developed oilseed varieties with high oleic, low linolenic fatty acid profile (HOLL) varieties which have high stable oil for the food processing industry and high erucic acid

(HEAR) varieties which are grown for specialist markets such as fine chemicals. Breeders have also developed oilseed rape varieties that combine fatty acid compositions that are applicable to the biodiesel industry and high seed yield, with 14 out of 37 Polish genotypes analysed by Kaczmarek *et al.*, (2008) shown to be satisfactory for the chemical industry and 10 genotypes satisfactory for biodiesel industry.

Plant breeders have increased the oil content of oilseed rape, with analysis of UK variety trials by Mackay *et al.*, (2010) demonstrating that genetic improvement has raised average oil content from about 42% to 44% between 1979-2007. The extent to which plant breeders have altered the oil content of oilseed rape varies between European countries, with UK breeders primarily focusing on increasing oil content and oil yield of oilseed rape, whilst in France improving both the oil and protein has been a major breeding target (Weightman *et al.*, 2014).

Use of rapemeal in livestock diets is limited by the fact that oilseed rape contains high levels of anti-nutritive factors such as fibre, phenolic acids, phytate and glucosinolates (Wittkop *et al.*, 2009). This could potentially be addressed by selecting for seed coat thickness and colour traits i.e. thin seed coat, yellow seed-types which would provide oilseed rape with higher oil and protein content and lower levels of ANF, although this is complex as the colour trait may not be stable between generations (Weightman *et al.*, 2014).

### Field beans

Our review suggests that plant breeders have aimed to improve field bean quality by reducing ANF present within field beans such as tannins. Genes linked to a reduction in tannin levels (zt-1 and zt-2) have been identified, with zt-2 also associated with increased protein levels and energy values and reduced fibre content of seed (Gutierrez *et al.*, 2007; Gutierrez *et al.*, 2008). Plant breeders have also aimed to develop field beans with low vicine and convicine levels by introgressing the spontaneous mutant allele named vc, which induces a 10-20 fold reduction of vicine and convicine contents into field bean cultivars (Gutierrez *et al.*, 2006). This is important as vicine and convicine are toxic glycosides that can cause favism in individuals who have a hereditary loss of the enzyme glucose-6-phosphate dehydrogenase and reduce animal performance (Gutierrez *et al.*, 2006). Plant breeders have also developed markers linked to gene traits affecting the nutritional value of seeds, which may facilitate a more efficient selection of new cultivars free of anti-nutritional compounds in the future (Torres *et al.*, 2010). Through the BEANS4FEEDS project (2012-2016), plant breeders also aim to widen the market for field beans by developing varieties that are better suited to air classification of flour so that field beans can be included in both ruminant and non-ruminant diets.

Another objective of plant breeders is to increase the methionine content of field beans. Methionine is an essential amino acid that is necessary for protein synthesis and has to be provided in the diet as it is not synthesised *de novo* in humans. Research from Schumacher *et al.*, (2009) found a positive correlation between high methionine content and chlorophyll content in field beans suggesting that chlorophyll content could be a putative selection trait involved in breeding field beans with high methionine content.

### Herbage

Quality traits have become increasingly important targets for herbage breeding programmes, with herbage quality relating to dry matter content, energy content, starch content and

digestibility (D value) (Humphreys *et al.*, 2006; Stewart and Hayes, 2011). Improvements in *in vitro* dry matter digestibility of intermediate heading diploid perennial ryegrasses have been made (Wilkins and Lovatt, 2011) as well as improvements in water soluble carbohydrate (WSC) levels (Abberton, 2008) and there has been focus on breeding hybrid forage legume varieties which have improved cell wall degradability (Courtial *et al.*, 2014). Plant breeders are currently targeting improved polyunsaturated fatty acids (PUFA) contents in perennial ryegrass crops through the LipiGrass project which is a five year collaborative project between Aberystwyth University, Germinal Seeds and Hybu Cig Cymru (HCC), funded through the BBSRC LINK scheme.

Improving  $\alpha$ -linolenic acid transfer from herbage to ruminant products has also received some breeding focus (Scollan *et al.*, 2005) as  $\alpha$ -linolenic acid contributes to improved flavour of beef and lamb and has been linked to reducing cardiovascular disease risk in humans (Kandasamy *et al.*, 2008), with targets such as increasing the level of  $\alpha$ -linolenic acid in the forage, reducing the loss of polyunsaturated fatty acids (PUFA) during field wilting and reducing the extent of ruminal lipolysis and biohydrogenation (Scollan *et al.*, 2005). Breeding low oestrogen lines to reduce impact of phytoestrogens present in red clover on livestock fertility has also been a breeding objective (Marley *et al.*, 2011).

### Sugar beet

In sugar beet, the main improvement to crop quality has been via targeting bolting resistance to help extend the sugar beet sowing season (Chiurugwi *et al.*, 2013; Mutasa-Gottgens *et al.*, 2009), with QTL for post-winter bolting resistance found (Pfeiffer *et al.*, 2014).

### Resistance to lodging

Lodging is defined as the permanent displacement of a stem or stems from a vertical posture (Sylvester-Bradley *et al.*, 2008). Resistance to lodging can help to maximise harvestable yield by reducing harvest losses (HGCA, 2005).

### Wheat

Resistance to lodging can help to maximise harvestable yield by reducing harvest losses (HGCA, 2005) and has been a breeding target across all crop groups studied. In wheat, plant height variation in European winter wheat cultivars is mainly controlled by the Rht-D1 and Rht-B semi-dwarfing genes, but also by other medium- or small-effect QTL and potentially epistatic QTL enabling fine adjustments of plant height (Würschum *et al.*, 2015; Zanke *et al.*, 2014). Breeders have succeeded in breeding high yielding varieties with lodging resistance (Marshall *et al.*, 2013), although there is some evidence to suggest that lodging risk in wheat varieties introduced since 2000 has increased due to increases in yield potential without any further plant shortening (Berry *et al.*, 2014).

### Barley

Resistance to lodging is a key criterion on the winter and spring barley AHDB Recommended List 2014-2015 with lodging resistance scores ranging from 5-8 for both winter and spring barley varieties (HGCA 2015c; HGCA 2015f).

### Oats

Modern oat varieties have good lodging resistance, with lodging resistance scores on the Winter Oat AHDB Recommended List 2015-2016 ranging from 4-9 for conventional husked varieties and

ranging from 5-9 for winter naked varieties (HGCA, 2015d). Eight dwarfing genes have been found in oats, although only three of these: DW6, Dw7 and DW8 have proven useful in the breeding of new oat varieties (Marshall *et al.*, 2013). Plant breeders aim to develop oat varieties with good lodging resistance and high yields, with the introduction of the winter oat variety Balado to the UK winter oat AHDB/HGCA Recommended List in 2010 evidence of success in this area (Marshall *et al.*, 2013).

### Oilseed rape

Lodging resistance is a high priority trait for oilseed rape breeders and has been identified by farmers and agronomists as the second most important varietal trait after yield potential (Spink and Berry, 2005). Lodging resistance, stem stiffness and shortness of stem are traits tested under AHDB/HGCA Recommended List trials, with all varieties recommended for use in the north, east and west having a lodging resistance score of 7+ on the AHDB/HGCA Recommended List (HGCA 2015h).

### Field beans

Little scientific evidence was found of research into further improving lodging resistance in field beans. However, standing ability is a trait measured as part of the Pulse Growers Research Organisation (PGRO) Field Bean Recommended Lists 2015 (PGRO, 2015).

### Field peas

Historically, there has been some improvement in standing ability of field peas, with severe lodging only estimated to take place one year in four due to improvements in standing ability of commercial pea varieties (Weightman, 2005), partly due to the introduction on the *afila* gene (*af*) in the mid 1970's, which results in additional tendrils replacing leaflets, and was responsible for a substantial improvement in the standing ability of the crop. Despite these improvements, standing ability of the pea crop is still a problem and is associated with harvesting difficulty and has been identified as a high priority trait by breeders.

### Forage Maize

Standing ability is a criterion tested under the Forage Maize Descriptive List funded by BSPB and NIAB, with an average standing ability score of 8.2 out of a maximum of 9 across all varieties and a lodging percentage score (%) of between 0.5-0.6% across varieties (Forage Maize Descriptive List, 2015).

## Resistance/tolerance to diseases

Resistance and tolerance to diseases are key to protecting crop yield. Resistance to diseases is defined as '*the reduction of growth of a pathogen on or in the plant*', whilst disease tolerance is the '*heritable capacity of a crop to maintain yield in the presence of disease*'. Our review has identified that disease resistance/tolerance has been a major driver behind EU and UK plant breeding objectives to help protect against yield losses and there have been successes in breeding for resistance to diseases across crop groups.

### Wheat

Key diseases that affect wheat crops in the UK include *Septoria tritici* blotch (*Zymoseptoria tritici*), fusarium, mildew, yellow rust (*Puccinia striiformis f.sp. tritici*), brown rust (*Puccinia triticina*),

eyespot and *Phaeosphaeria nodorum* formally *Septoria nodorum*. The success of breeders to produce varieties with resistance to these diseases is discussed below.

### **Resistance to *Septoria tritici* blotch**

In wheat, disease resistance has focused on the main economically damaging diseases such as septoria tritici blotch (caused by *Zymoseptoria tritici*), fusarium and rust. Genes which increase resistance to *Z. tritici* have been identified on 21 chromosomes in wheat (Brown, 2012b), with the Stb6 resistance gene and Stb11 gene associated with a reduction in the level of *S. tritici* leaf blotch (Arraiano *et al.*, 2009; Radecka-Janusik *et al.*, 2014) and these have been introgressed into modern varieties. (HGCA, 2015f). The use of biotechnology-based research and improved understanding the complexity of wheat's and the dynamism of *Z. tritici*'s genome, has also helped to reduce threat of *septoria tritici* blotch disease in wheat-production systems (O'Driscoll *et al.*, 2014).

### **Resistance to fusarium**

In wheat, fusarium resistance is good, with most varieties in the AHDB/HGCA Winter Wheat Recommended List 2015-2016 having a fusarium resistance score of 6 or 7 (HGCA 2015i). Work is underway to maintain fusarium resistance, with resistance QTL for fusarium head blight found on chromosomes 1B and 2B (Nicholson, 2013) and identification of the Rht1 and Rht2 genes which are linked to Type I (resistance to initial infection) and Type II (resistance to infection spread within infected tissue) fusarium resistance (Nicholson *et al.*, 2008). Recent research has shown that allelic variation in two homologous NPR1-like genes is associated with fusarium head blight resistance in European winter wheat, which could be used in marker-assisted breeding programs (Diethelm *et al.*, 2014). However, breeding progress towards fusarium resistance is constrained by the fact there is a negative trade-off between disease resistance and other desirable traits, with higher yields often associated with greater loss per unit disease (Paveley *et al.*, 2005). In addition, varieties with the Rht-D1b gene are more susceptible to fusarium infection than those without this gene (Knopf *et al.*, 2008; Miedaner *et al.*, 2011), and as such overcoming these negative associations is an ongoing breeding objective.

### **Resistance to yellow and brown rust**

Yellow rust, caused by the fungus *Puccinia striiformis f.sp. tritici*, and brown rust, caused by the fungus *Puccinia triticina* are two of the UK's major wheat diseases, with failure to control these diseases resulting in yield losses of up to 50% (HGCA, 2012c). QTLs for yellow rust resistance have been found at four different genomic locations on chromosome 2AL, 2AS, 2BL and 6BL (Christiansen *et al.*, 2006), with two of these QTL on chromosome 2A being identical to known yellow rust resistance genes *Yr32* and *Yr17*, whilst the QTLs found on 2B and 6B reflected new forms of resistance. The *Yr36* locus has also suggested to be a potential effective source of partial resistance in temperate wheat growing regions (Segovia *et al.*, 2014). Work has also been carried out using association genetics to map genes contributing to specific and partial rust resistance in UK wheat varieties (Hudcovicova *et al.*, 2008) to better understand the genetic basis of rust resistance. Developing durable resistance to rust is a target of plant breeders as there has been repeated appearance of new yellow rust races which challenges existing varietal resistance. An example of this is the 'Warrior race' of yellow rust which was first recorded in 2011 and has

virulence to the resistance genes Yr1,Yr2,Yr3,Yr4,Yr6,Yr7,Yr9,Yr17,Yr32, with varieties such as Oakley being particularly susceptible (Hubbard and Bayles, 2013).

#### **Resistance to *Phaeosphaeria nodorum***

*Phaeosphaeria nodorum* was once the most serious pathogen on cereals in the UK, although it now rarely causes significant losses except in wet seasons in the south west of England. Yield losses up to 50% have been reported in trials, although average annual losses in the UK are thought not to exceed 3% (HGCA, 2008). Resistance to *P. nodorum* is a trait tested under AHDB/HGCA Recommended List trials, with suggested resistance scores in the winter wheat AHDB/HGCA Recommended List 2015-2016 ranging from 5-6 (HGCA 2015i).

#### **Resistance to mildew**

Mildew is caused by *Blumeria graminis*, with symptoms of mildew found on leaves, stems and ears (HGCA, 2008). Little scientific literature was found focusing on resistance to mildew as a specific breeding objective, however 75% of the varieties listed on the winter wheat HGCA Recommended List 2015-2016 have a resistance score of 6 or above and 21% varieties have a resistance score of 8 or 9 (HGCA, 2015f).

#### **Resistance to Eyespot**

Eyespot is caused by *Oculimacula yallundae* (W-type) and *O. aciformis* (R-type) which infect stem bases and reduce water and nutrient uptake causing lodging and associated yield losses (HGCA, 2012b). Some work has been done on improving eyespot resistance in wheat (Burt *et al.*, 2014), although deployment of eyespot resistance was slowed due to the fact that the Pch1 gene for eyespot is on a chromosome segment that also reduces yield and inhibits the use of Pm16 gene for resistance to powdery mildew (Summers and Brown, 2013).

#### **Resistance to Take-all**

Take-all, caused by *Gaeumannomyces graminis*, is a major soil-borne root disease of wheat causing progressive root rotting and yield loss via reduced water and nutrient uptake and premature ripening (HGCA, 2008). There are currently no commercial UK wheat varieties with specified take-all resistance, however, one of the objectives of the Wheat Genetic Improvement Network (WGIN) is to develop take-all resistance in commercial cultivars. WGIN aims to provide genetic and molecular resources for research for a wide range of wheat research projects in the UK targeting specific traits such as disease resistance, insecticide resistance and drought tolerance. In addition, research has shown that some commercial wheat genotypes consistently exhibit reduced levels of moderate and severe take-all and work has been undertaken to characterise the germplasm of these varieties for use in breeding programmes (Gutteridge, 2008).

#### **Resistance to Soil-Borne Cereal Mosaic Virus (SBCMV)**

Soil-Borne Cereal Mosaic Virus (SBCMV) is transmitted by the soil-borne protist *Polymyxa graminis* and can cause serious yield losses in susceptible wheat cultivars (Bayles *et al.*, 2007). Resistant cultivars are the main possibility of controlling SBCMV, as most chemical control is ineffective. There are currently no commercial varieties in the UK which have specific SBCMV resistance, although two major SBCMV resistance genes have been identified, Sbm1, on chromosome 5DL and Sbm2, on chromosome 2BS. Lines carrying both genes have been shown

to have lower virus levels than lines carrying either gene alone, implying that the two resistances act in distinct and complementary ways to limit viral spread (Bayles *et al.*, 2007). Amplified fragment length polymorphism (AFLP) markers have also been identified within ~1 centromere (cM) of Sbm1 and Sbm2 which can be used to select for SBCMV resistant varieties in breeding programmes (Defra, 2006).

## Barley

Developing barley varieties with resistance/tolerance to diseases has been a major objective of plant breeders (Ordon *et al.*, 2005). Diseases that affect barley include mildew, yellow rust (*Puccinia striiformis f.sp. tritici*), brown rust (*Puccinia triticina*), rhynchosporium (*Rhynchosporium secalis*), ramularia (*Ramularia collo-cygni*) and net blotch (*Pyrenophora teres*). Breeding progress towards resistance/tolerance to these diseases is discussed below.

### Resistance to mildew

Commercial barley varieties have resistance to mildew (HGCA 2015a; HGCA, 2015c). Such high levels of resistance are suggested to be as a result of wide use of effective resistance genes such as Mlo and use of marker assisted selection (MAS) for targeting resistant genes (Dreiseitl, 2007).

### Resistance to yellow and brown rust

Commercial barley varieties have resistance to yellow rust (*Puccinia striiformis f.sp. tritici*) and brown rust (*Puccinia triticina*), with around 70% of winter barley varieties having a yellow rust resistance score of 6 or above compared to around 60% of spring barley varieties on the AHDB/HGCA Recommended List 2015-2016. Around 80% of winter barley varieties have a brown rust resistance score of 6 or above compared to around 28% of spring barley varieties on the AHDB/HGCA Recommended List (HGCA 2015c; HGCA 2015f).

### Resistance to Ramularia

Ramularia leaf spot is caused by the fungus *Ramularia collo-cygni* which grows through the plant from the infected seed with visible lesions usually produced around flowering or shortly after (HGCA, 2014d). Around 60% of spring barley varieties listed on the AHDB/HGCA Spring Barley Recommended List 2015-2016 have a resistance score of 6 or above for ramularia, with four varieties having a suggested resistance score of 8 (HGCA 2015c). There can be a trade-off between resistance to mildew and resistance to ramularia with presence of the mlo5 gene suggested to increase the varietal susceptibility to ramularia, particularly where the variety is stressed by light (Oxley *et al.*, 2008). Improving ramularia resistance is a target for plant breeders with a current AHDB/HGCA project (Brown, 2012a) focusing on how to reduce losses to ramularia leaf spot underway (RAMularia leaf spot in a Changing CLimatE (CORACLE)).

### Resistance to Barley yellow mosaic virus (BaYMV) and barley mild mosaic virus (BaMMV)

Barley yellow mosaic virus (BaYMV) and barley mild mosaic virus (BaMMV) are transmitted by the plasmodiophorid fungus *Polymyxa graminis* which can cause yield losses of up to 50% in susceptible varieties (HGCA, 2008). The Rym4/Rym5 gene locus confers resistance to the barley yellow mosaic virus complex (Tyrka *et al.*, 2008) and modern barley cultivars have good resistance against barley mild mosaic virus (BaMMV) and to barley yellow mosaic virus (BaYMV) (HGCA 2015f).

### Resistance to rhynchosporium

Rhynchosporium, caused by the fungus *Rhynchosporium commune*, regularly occurs on barley in wetter parts of the UK, particularly southwest and northern England, Scotland and Northern Ireland and can lead to yield losses of up to 40%. Resistant varieties and use of fungicides are the main ways to control rhynchosporium (HGCA, 2011b), with durable rhynchosporium resistance a key breeding objective, with over half of winter and spring barley varieties having a resistance score of 6 or above for rhynchosporium (HGCA 2015c; HGCA 2015f). An AHDB/HGCA project (RD-2012-3773) is underway to match *R. commune* genes with known barley R genes and select candidate fungal genes useful for identification of novel sources of resistance to rhynchosporium in the future (HGCA, 2012a).

### Resistance to Net Blotch

Net blotch, caused by the fungus *Pyrenophora teres* is spread by air-borne spores and rain splash with affected leaves having short brown stripes or blotches with a network of darker lines present (HGCA, 2008). Commercial barley varieties have resistance to net blotch, with around 40% of winter barley varieties on the AHDB/HGCA Recommended List 2015-2016 having a resistance score of 6 or above for this disease (HGCA 2015f).

### Oats

Plant breeders have targeted improvements in crown rust, mildew and fusarium resistance of oats, with resistance scores to crown rust and mildew given in the winter and spring oats AHDB/HGCA Recommended List 2015-2016 (HGCA, 2015b; HGCA 2015d). The QUOATS project also aims to breed for durable crown rust and mildew resistance in oats. Commercial varieties with fusarium resistance are not currently available in the UK, although recent work has identified a QTL for deoxynivalenol (DON) on chromosome 17A/7C, tentatively designated as Qdon.umb-17A/7C, and a QTL for DON on chromosomes 5C, 9D, 13A, 14D and unknown\_3 which will be useful for future breeding programmes (He *et al.*, 2013).

### Oilseed rape

Plant breeders have targeted resistance to phoma stem canker and light leaf spot in oilseed rape, with commercial varieties with resistance to these diseases available in the UK (HGCA, 2015e). Other diseases that affect oilseed rape include sclerotinia, alternaria, powdery mildew and verticillium wilt, with the variety Trinity suggested to have a degree of verticillium resistance compared to more susceptible varieties such as Laser or Falcon (Elsoms, undated), although resistance to verticillium is not a criterion currently recognised on the AHDB/HGCA Recommended List.

### Resistance to phoma stem canker

Phoma stem canker is caused by *Leptosphaeria maculans* and is a major disease of oilseed rape crops, with later sown crops more at risk. Two types of resistance against *L. maculans* have been identified; major resistance (R) gene-mediated qualitative resistance and quantitative resistance, specific resistance genes to phoma stem canker have been found (e.g. Rlm4, Rlm7) and QTLs for disease resistance (LmA2 and LmA9) have been seen in the French oilseed rape variety 'Darmor' (Delourme *et al.*, 2008). Varietal resistance to phoma stem canker is available; around 35% of winter oilseed rape varieties that are on the AHDB/HGCA Winter Oilseed Rape Recommended

List 2015-2016 for the North and for the East and West suggested to have a phoma stem canker resistance score of 6 or above (HGCA 2015h). Research by West *et al.*, (2008) has aimed to improve breeding for varieties showing stem canker resistance by potentially producing new methods to rate cultivar resistance to stem canker such as via recording the percentage of canker (either as area or girdling) as a continuous variable, rather than on the 0-6 scale currently used in AHDB/HGCA Recommended List assessments, although this would be more time consuming to complete.

#### **Resistance to light leaf spot**

Light leaf spot, caused by *Pyrenopeziza brassicae*, is a damaging disease of oilseed rape. Good control with fungicides is difficult to achieve and greater use of cultivars with resistance against the causal pathogen seen as essential to manage the disease (HGCA, 2015b). All winter oilseed rape varieties on the AHDB/HGCA Winter Oilseed Rape Recommended List 2015-2016 for the North and around 54% of varieties that are on the AHDB/HGCA Winter Oilseed Rape Recommended List 2015-2016 for the East and West have a light leaf spot resistance score of 6 or above, indicating good resistance (HGCA 2015h). A PhD project is underway, funded by AHDB/HGCA, which aims to sequence a major resistance gene on chromosome A1 and to use the sequence of the resistance gene to identify other light leaf spot resistance genes in commercial oilseed rape cultivars. Once this is done the project aims to generate markers for marker assisted selection of these genes in oilseed rape breeding programmes (HGCA, 2014b).

#### **Resistance to Verticillium wilt**

Verticillium wilt, caused by *Verticillium longisporum*, is an important disease in oilseed rape in European countries, particularly Sweden and Germany and can cause yield losses up to 50% in Europe. Crop rotation remains the main method of verticillium wilt control (Gladders, 2009), however, the seed and plant breeding company, Elsoms claim to have bred a variety called Trinity which has a degree of verticillium resistance (Elsoms, undated). At the pre-commercial level, QTLs on four different chromosome regions from resistant parent 307-230-2 have been identified (Rygulla *et al.*, 2008), with genes from the phenylpropanoid pathway thought to be candidates for *V. Longisporum* resistance (Obermeier *et al.*, 2013) which could be used in future breeding programmes.

#### **Resistance to clubroot**

Clubroot, caused by the pathogen *Plasmodiophora brassicae*, is an increasing problem in oilseed rape crops throughout the UK, with yield losses of 0.3 t/ha for every 10% of clubroot severity which can amount to 50% of yield potential in severely affected crops (HGCA, 2011a). The AHDB/HGCA Recommended Lists for oilseed rape do not give resistance scores for club root, however, existing varieties do show differences in club root resistance with Mendel and Cracker shown to give 65- 99% disease control at three sites in the West Midlands (Warwickshire, Shropshire and Hereford) in six trials over three seasons (Burnett *et al.*, 2013). There are also commercial varieties in the UK with resistance to club root e.g. SY ALISTER from Syngenta. QTLs linked to club root resistance have been found on chromosomes giving resistance to seven different isolates, although none of the QTL identified confer resistance to all *P. brassicae* isolates (Werner *et al.*, 2008).

## Field beans

Major diseases of field beans include leaf and pod spot (*Ascochyta fabae*), rust (*Uromyces viciae-fabae*), chocolate spot (*Botrytis fabae*), downy mildew (*Peronospora viciae*), foot rots (*Fusarium spp.*), common bacterial blight (CBB) and Sclerotinia stem rot, a fungal disease caused by *Sclerotinia trifoliorum* (Lithourgidis *et al.*, 2004). There has been some work developing commercial varieties with resistance to leaf and pod spot and downy mildew, although compared to cereal crops little progress has been made for selecting for disease resistance traits in field beans in the UK. There is scope to improve this; molecular breeding for resistance to leaf and pod spot (*A. fabae*), rust (*U. viciae-fabae*) and chocolate spot (*B. fabae*) is underway, (Torres *et al.*, 2010), with Random Amplified Polymorphic DNA (RAPD) markers linked to a gene determining hypersensitive resistance to race 1 of the rust fungus *U. viciae-fabae* found (Torres *et al.*, 2006).

### Resistance to Leaf and Pod Spot (*Ascochyta fabae*)

Leaf and pod spot, caused by the fungus *Ascochyta fabae*, is seed-borne, air-borne and splash dispersed and can produce brown spots containing distinctive black fruiting bodies on infected plants (PGRO, 2014). Resistance to *A. fabae* is a criterion as part of the PGRO Recommended List (PGRO, 2015). Six QTLs, namely af3- af8, linked to *A. fabae* resistance have been found, with Af3 and Af4 conferring resistance to two types of *Ascochyta* isolates (Avila *et al.*, 2004). Commercial field bean cultivars from France and the Czech Republic have been shown to be susceptible or highly susceptible to anthracnose caused by the fungus *Ascochyta fabae* Speg suggesting that further improvement of resistance of commercial cultivars to *A. fabae* can still be made, particularly in white flowering field beans (Ondrej and Hunady, 2007).

### Resistance to downy mildew (*Peronospora viciae*)

Plant breeders have successfully bred for downy mildew (*Peronospora viciae*) resistance in spring field beans (PGRO, 2015). Research suggests that there is scope to improve downy mildew resistance in commercial varieties as plant breeders currently have little information on the sources of resistance or its genetic control and large-scale evaluation of field bean germplasm for resistance to downy mildew has not yet been carried out.

### Resistance to chocolate spot

Chocolate spot is caused by *Botrytis cinerea* and *B. fabae* and has been reported to be the cause of yield reductions in the UK (Syngenta, 2013). A number of sources of resistance to *B. cinerea* and *B. fabae* have been reported, but most have not yet been introduced into commercial varieties, with the lack of good resistance sources limiting breeding progress.

## Field peas

Key diseases that affect pea crops include pea wilt (*Fusarium oxysporum f. sp. pisi*), downy mildew (*Peronospora viciae*), leaf and pod spots (*Ascochyta pisi*, *Mycosphaerella pinodes* and *Phoma medicaginis*), botrytis (*Botrytis cinerea*), powdery mildew (*Erysiphe pisi*), root rots (*Fusarium solani f. sp. pisi*, *Phoma medicaginis var. pinodella*), Sclerotinia (*Sclerotinia sclerotiorum*) and bacterial blight (*Pseudomonas syringae pv. pisi*). Breeding progress towards resistance to these diseases is shown below.

### **Resistance to pea wilt**

In peas, there has been some breeding focus on improving resistance of modern field pea varieties to pea wilt (Rispaill and Rubiales, 2015) which is a soil borne disease caused by *Fusarium oxysporum f. sp. Pisi.*, with commercial UK varieties showing pea wilt resistance (PGRO, 2015), and resistance mechanisms to races 1, 5, and 6 of *F. oxysporum* and resistance to race 2 identified (Bani *et al.*, 2014).

### **Resistance to downy mildew (*Peronospora viciae*)**

Downy mildew is prevalent on spring beans where it causes greyish-brown growth on the under-surface of the leaves (PGRO, 2014). Little scientific evidence was found focusing on improving resistance to downy mildew in peas, although commercial UK spring bean varieties have resistance to this disease (PGRO, 2015).

### **Resistance to powdery mildew (*Erysiphe pisi*)**

Powdery mildew, caused by the ascomycete fungus *Erysiphe pisi*, is characterised by irregular areas of powdery white fungal growth on the upper leaf surface and pods and can delay pea maturity (PGRO, 2014). Three genes, er1, er2 and er3, conferring resistance to powdery mildew in pea and their molecular markers have been found (Fondevilla *et al.*, 2008; Ek *et al.*, 2005). The genetic and phytopathological features of er1 resistance are similar to those of other plants such as barley, Arabidopsis, and tomato which aids breeders in developing resistant cultivars via marker-assisted selection (Pavan *et al.*, 2011), although this is not currently a criterion recognised on the PGRO pea Recommended List.

### **Resistance to Ascochyta blight**

Ascochyta blight, caused by *Mycosphaerella pinodes*, is one of the most damaging necrotrophic pathogens of field peas worldwide causing losses in both yield and quality in wet conditions (Le May *et al.*, 2014). Breeding for resistance has been limited, with only intermediate levels of resistance available in commercial cultivars and resistance more common in *Pisum* relatives (Fondevilla *et al.*, 2008). There is little known about mechanisms underlying resistance to *M. pinodes* during infection, although recent research has shown that resistance might be linked to jasmonic acid (JA) and ethylene signal transduction pathways (Fondevilla *et al.*, 2011).

### **Resistance to bacterial blight**

Bacterial blight, caused by *Pseudomonas syringae pv. Pisi* can cause stem based lesions which become noticeable following periods of heavy rain, hail or frost and can lead to pod spotting. Severe infections have not occurred in spring peas in the UK and to date the effect on yield has been negligible (PGRO, 2014). Little UK scientific research was found focusing on breeding for resistance to bacterial blight, although research in Spain found R2, R3 and R4 race specific resistance genes to *P. syringae pv. pisi* reduced bacterial blight severity in pea plants in the field (Martin-Sanz *et al.*, 2012).

### **Resistance to pea seed-borne mosaic virus (PSbMV)**

Resistance to pea seed-borne mosaic virus (PSbMV) is conferred by a single recessive gene (eIF4E), localized on LG VI (sbm-1 locus) (Smykal *et al.*, 2010). To date, plant breeders have identified the eIF4E gene structure and mutations responsible for PSbMV resistance and developed gene-specific single nucleotide polymorphism and co-dominant amplicon length

polymorphism markers which will speed up PSbMV diagnosis and resistance breeding processes (Smykal *et al.*, 2010).

## Herbage

Ryegrasses are affected by a number of diseases including Ryegrass Mosaic Virus (RgMV), Barley Yellow Dwarf Virus (BYDV) (DairyCo, 2012), mildew, crown rust (*Puccinia coronata*), drechslera and rhynchosporium. Disease resistance has been a target of ryegrass breeders, with most varieties of perennial ryegrass having a degree of resistance to crown rust, drechslera and mildew, most Italian ryegrass varieties having resistance to crown rust (*P. coronata*), brown rust (*P. tritricina*), RgMV, mildew, and rhynchosporium and most hybrid ryegrasses having a degree of resistance to RgMV and mildew as shown in the Grass and Clover Recommended Lists 2015 (British Grassland, 2015).

### Resistance to crown rust (*P. coronata*)

Targeted breeding in perennial ryegrass has improved crown rust resistance, with improvement reaching +11.39% per decade over the last four decades relative to the cultivar set mean (Sampoux *et al.*, 2011). Research conducted throughout Europe as part of the European Association for Research on Plant Breeding (EUCARPIA) also suggests that crown rust resistance is relatively durable in European cultivars with crown rust resistance scoring staying constant over the seven year assessment period (Schubiger *et al.*, 2010).

### Resistance to powdery mildew

Our review suggests that breeding cultivars with resistance to powdery mildew has also been a target of plant breeding, with QTL for powdery mildew resistance in perennial ryegrass found (Schejbel *et al.*, 2008).

### Resistance to bacterial wilt (*Xanthomonas translucens pv. graminis*)

Cultivars from Switzerland have been bred with a degree of resistance to bacterial wilt, caused by *Xanthomonas translucens pv. graminis* (Xtg), and a single major QTL on linkage group (LG) 4 which accounts for 67% of the total phenotypic variance in susceptibility to Xtg identified, with a minor QTL also observed on LG 1,4, 5 and 6. (Studer *et al.*, 2006).

### Resistance to other ryegrass diseases

Little scientific evidence was found from the last ten years in the UK or wider Europe relating to breeding for Barley Yellow Dwarf Virus (BYDV), rhynchosporium, drechslera resistance in ryegrass crops, despite the potential losses in yield and persistence being demonstrated (DairyCo, 2012).

## Forage Maize

Our review suggests that there has been some work carried out on breeding for resistance to diseases in forage maize. Resistance to eyespot (*Aureobasidium zeae*) was introduced as a criterion on the Forage Maize Descriptive List in 2015, with over 70% of varieties for favourable and less favourable sites having a degree of resistance to this disease (BSPB, 2015). Fusarium resistance is an important breeding goal (Bolduan *et al.*, 2010), however breeding for fusarium resistance is complicated by significant genotype × environment interaction ( $P < 0.01$ ) (Loffler *et al.*, 2010) which slows breeding progress in this area.

## Sugar beet

Diseases that can affect sugar beet include rhizomania, powdery mildew (*Erysiphe betae*), rust, Rhizoctonia root and crown rot caused by *Rhizoctonia solani*, leaf spot, Beet Mild Yellowing Virus (BMV) and Beet Yellows Virus (BYV).

### Resistance to rhizomania

In sugar beet, breeding progress has been made towards improving resistance to rhizomania which is induced by beet necrotic yellow vein virus, BNYVV, which is transmitted via the obligate root parasite plasmodiophoromycete *Polymyxa betae* (Asher *et al.*, 2009). Resistant varieties are the only available control method, with the variety, KWS Sandra showing resistance to the virulent strain (AYPR) of rhizomania. Rz1 is the major resistance gene present within commercial sugar beet varieties, although Rz2 and Rz3 genes are also linked to rhizomania resistance (Gidner *et al.*, 2005). QTL analysis in a sugar beet mapping population has also identified a novel resistance source (Rz4), located on chromosome III (Grimmer *et al.*, 2007). A gene designated as Rz5 has also been mapped at the same location as Rz1 and Rz4, indicating that these genes might represent different alleles (Grimmer *et al.*, 2008c). In addition to searching for new genes against BNYVV, improving disease resistance has also been pursued by means of exploiting probable resistance to the transmitting vector, *P. betae*, itself, with a QTL (Pb1) for resistance to *P. betae* found to be co-localized on chromosome IV, indicating resistance to rhizomania is conditioned by vector resistance and this was shown to reduce *P. betae* levels in the F1 population through interaction with a second QTL (Pb2) found on chromosome IX (Asher *et al.*, 2009). Emergence of new BNYVV strains with increased virulence that could overcome Rz1 resistance have been found and as such, exploitation of new genetic sources of resistance and the pyramiding of several resistance genes into new breeding lines is becoming a main priority for sugar beet breeders to maintain resistance levels (de Biaggi *et al.*, 2010).

### Resistance to powdery mildew (*Erysiphe betae*)

Powdery mildew, caused by *Erysiphe betae*, can cause white or whitish mycelium to appear on the upper leaf surface and with severe infection, the leaves become pale green, yellow later and die. Resistant genotypes to powdery mildew have been identified in four beet types (fodder, garden, leaf and sugar beet) which use different resistance mechanisms acting at different fungal developmental stages i.e. penetration resistance, early and late cell death, or post-haustorial resistance (Fernández-Aparicio *et al.*, 2008). QTL analysis has also identified a single region on Chromosome IV conferring dominant resistance to powdery mildew and rust (James *et al.*, 2012). In addition, five dominant major resistance loci have been identified and assigned to the proposed symbols Pm2 to Pm6, with Pm3 conferring complete resistance to powdery mildew; and other loci conferring high levels of partial resistance (Grimmer *et al.*, 2007), although recent research has shown that pairwise combinations of different alleles of the powdery mildew resistance gene Pm3 in F1 hybrids and stacked transgenic wheat lines can result in suppression of Pm3-based resistance (Stirnweis *et al.*, 2014).

### Resistance to rust

Little scientific evidence was found relating to rust resistance, although resistance to rust is a criterion of the BBRO Sugar beet Recommended List 2016, with listed varieties having variable resistance scores ranging from 1 (KWS Tasmania) to 8 (KWS Sabatina).

### Resistance to *Rhizoctonia* root and crown rot

*Rhizoctonia* root and crown rot caused by the fungus *Rhizoctonia solani* is a serious disease of sugar beet. Three QTL for *R. solani* resistance have been found on chromosomes 4, 5 and 7 (Lein *et al.*, 2008), although no commercial UK sugar beet varieties have been bred with resistance to *R. solani*.

### Resistance to Beet Mild Yellowing Virus (BMV) and Beet Yellowing Virus (BYV)

Beet Mild Yellowing Virus (BMV) and Beet Yellowing Virus (BYV) are transmitted by aphids such as the peach potato aphid *Myzus persicae* and the black bean aphid *Aphis fabae* (Stevens *et al.*, 2005). There are currently no commercial, resistant varieties to BMV or BYV, making the use of insecticides the main control method. However, research by Grimmer *et al.*, (2008a) has shown that it is possible to introgress resistance genes from wild beet populations into elite sugar beet lines in future breeding programmes. There has been some research carried out focusing on selecting for BMV or BYV resistance with a significant region on chromosome IV identified by mapping analysis which controls the severity of yellowing symptoms induced by BMV infection (James *et al.*, 2012). Three BYV resistance QTLs have been identified and mapped to chromosomes III, V and VI, with results suggesting that chromosome III and V QTLs act only in plants with mosaic symptoms and that the chromosome VI QTL act only in plants with the mosaic symptom allele of Vc1 (Grimmer *et al.*, 2008b).

### Resistance to *Cercospora* leaf spot

Little UK evidence was found focusing on targeting resistance to leaf spot, although partially resistant varieties are available in Italy (Galletti *et al.*, 2008). Resistance to *Cercospora* leaf spot (*Cercospora beticola*) was assessed in up to 600 accessions of closely related wild and cultivated *Beta* species, with 1–12% of accessions highly resistant to this and other sugar beet diseases (Luterbacher *et al.*, 2004).

## Resistance/tolerance to pests

### Wheat

Wheat is affected by a number of pests including orange wheat blossom midge (OWBM, *Sitodiplosis mosellana*), grain aphid (*Sitobion avenae*), rose grain aphid (*Metopolophium dirhodum*), grey field slug (*Deroceras reticulatum*), gout fly (*Chlorops pumilionis*), wheat bulb fly (*Delia coarctata*), yellow cereal fly (*Opomyza florum*), saddle gall midge (*Haplodiplosis marginata*), wireworms (*Agriotes lineatus*, *Agriotes obscurus*) and leatherjackets (*Tipula paludosa*, *Tipula oleracea*) (HGCA, 2003).

The main breeding success for pest resistance across all crop groups studied was the introduction of orange wheat blossom midge (OWBM) resistance in wheat. OWBM resistance is affected by the gene Sm1 which is located on chromosome arm 2BS, although other chromosomes may also influence resistance (Ellis *et al.*, 2009). Plant breeders have successfully transferred OWBM resistance into milling wheat lines, with the winter milling wheat variety Skyfall and the spring milling wheat variety Mulika believed to be resistant to OWBM. Aphid resistance is a goal of the Wheat Genetic Improvement Network (WGIN) and there has also been initial research targeting resistance to the grain aphid *Sitobion avenae* (F.) with the resistant diploid line ACC20 PGR1755 identified as a potential resource in breeding wheat for resistance to aphids (Guan *et al.*, 2015).

## Barley

Our review has found very little evidence focusing on developing barley varieties with pest resistance. Research in Germany on resistance to the root-lesion nematode *Pratylenchus neglectus* has found varietal differences in multiplication rates of *P.neglectus* and identified five QTLs linked to these differences (Sharma *et al.*, 2011), however resistance to *P.neglectus* is not available in commercial UK varieties.

## Oilseed rape

The main pest that has received breeding focus in oilseed rape is Turnip Yellow Virus (TuYV) which is transmitted by *Myzus persicae*. QTL linked to TuYV resistance have been identified (Stevens *et al.*, 2008) and in the UK the commercial variety 'Amalie' is available with TuYV resistance. In addition, varietal differences in TuYV susceptibility have been found, with TuYV shown to decrease yield significantly in NK Grace, Emerson, DK Secure & DK Sequoia ( $p=0.004$ , 0.023, 0.027, 0.045 respectively) and cause a significant decrease in oil content in Emerson, Amillia, Flash ( $p<0.05$ ) (Coleman *et al.*, 2014).

## Field Beans

The main pests that affect field bean crops include pea and bean weevil (*Sitona lineatus*), black bean aphid (*Aphis fabae*), stem nematode (*Ditylenchus gigas*, *D. dipsaci*) and bean seed weevil (*Bruchus rufimanus*). There are currently no varieties with stem nematode resistance available which are appropriate for use in the UK. A project funded by Innovate UK and supported by the Sustainable Agriculture and Food Innovation Platform (SAF-IP) is also being carried out which aims to identify genes conferring stem nematode resistance and to select for these genes within current breeding programmes (O'Sullivan *et al.*, 2010). In addition, a PGRO co-ordinated project supported by the Sustainable Agriculture and Food Innovation Platform (SAF-IP) aims to use single nucleotide polymorphism (SNP) genotyping and rapid screening procedures to enable commercialisation of field bean varieties with stem nematode resistance (PGRO, 2013b).

## Field Peas & Herbage

This review found no evidence of pest resistance being a breeding objective in pea or herbage crops.

## Forage Maize

There has been limited work conducted in Europe in breeding for resistance/tolerance to pests in forage maize crops, although resistance to corn borer has been targeted internationally through the introduction of the Bt gene into forage maize crops (Royal Society, 2009). The European corn borer, *Ostrinia nubilalis* and the pink stem borer, *Sesamia nonagrioides* are the main pests affecting maize in Europe, although level of resistance to pink stem borer in modern forage maize varieties is not high (Butron *et al.*, 2006) and few studies have documented the mechanisms of resistance involved (Butron *et al.*, 2005). The creation of the European Union Maize Landrace Core Collection (EUMLCC) enabled screening for European corn borer resistance amongst European maize local populations from France, Germany, Greece, Italy, Portugal, and Spain, with findings suggesting that 'PRT0010008' and 'GRC0010085', among very early landraces; 'PRT00100120' and 'PRT00100186', among early landraces; 'GRC0010174', among midseason landraces; and 'ESP0070441', among late landraces performed well under corn borer infestation (Malvar *et al.*, 2004).

## Sugar beet

The beet cyst nematode (*Heterodera schachtii*) is the main sugar beet pest that has received breeding attention in the UK, with the tolerant variety Fiorenza KWS launched in the UK in 2009 and seven varieties currently on the BBRO Sugar Beet Recommended List 2016 having a degree of tolerance to beet cyst nematode (BCN). In wider Europe, resistant BCN varieties exist with varieties appropriate for UK conditions, such as Sannetta, starting to enter UK trials (Syngenta Seeds, undated).

## Resistance/tolerance to weeds

Little evidence was found of research carried out by plant breeders to improve resistance/tolerance to weeds. This is potentially because, unlike in disease and pest control, genetic solutions to weeds are more limited and as such chemical and cultural control measures remain the most effective options. Research has shown that increased crop competitiveness can indirectly influence weed control, with the more competitive cultivars being taller and having higher ground cover and light interception than less competitive cultivars (Drews et al., 2009). Andrew *et al.*, (2013) found that cereal seedling height one month after emergence had the most impact on black-grass (*Alopecurus myosuroides*) final biomass and seed return ( $p=0.0016$ ;  $p<0.001$ ) with longer flag leaves, higher rate of tillering and green leaf area also leading to a decrease in black-grass biomass and seed production. Nitrogen uptake is thought to influence crop competitiveness, with Ruisi *et al.*, (2015) finding that the ability of a crop to take up N from the soil can play a role in determining the different competitive abilities against weeds. Work by ADAS has also shown that the commercial barley variety, Volume has good competitive ability against black-grass, and can decrease black-grass head numbers by 79% compared with winter wheat (Cook, pers. comm). In oilseed rape, Clearfield technology is available which combines specifically bred herbicide tolerant hybrid seed with specific herbicides to give greater post-emergence broad spectrum activity on weeds such as charlock (BASF, undated).

## Raising Yields- Summary

- Plant breeders have met one of the targets of sustainable intensification by focusing on raising and protecting yield in major arable crops.
- Our review has demonstrated that most arable crops studied have shown an increase in yield over time due to plant breeding, with wheat yields increasing by 0.5 t/ha/decade over the last 50 years (Berry *et al.*, 2012) and oilseed rape yields increasing by 0.5 t/ha/decade since 1980 (Spink and Berry, 2005).
- Few advances have been made in improvement of field bean yields, with lack of market incentive limiting breeding attention. Research initiatives are underway to address this such as the Defra funded Pulse Crop Genetic Improvement Network (PCGIN) and the PROTYIELD project.
- Evidence found in this review suggests that pea yields have increased between 1993-2002 but no evidence was found highlighting yield improvements in the last decade despite traits linked to yield improvement being identified.

- Plant breeding has led to large improvements in forage maize, herbage and sugar beet yield, with genetic factors being responsible for 0.109 t/ha/year increase in forage maize yield between 1977-2007 and 0.105 t/ha/year increase in sugar beet yields between 1982-2007 (Mackay *et al.*, 2010).
- Plant breeders have improved crop quality across all crop groups in order to meet market requirements. Plant breeders have targeted crop quality parameters in milling wheat and malting barley which has improved efficiency of production and reduced crop wastage. In oats, field beans, field peas and herbage crops plant breeders have targeted improvements in nutritional quality and improved digestibility to promote use in livestock diets. The fatty acid content of oilseed rape has also been altered to develop varieties (HOLL, HEAR etc.) that are suited to specific end user requirements.
- Lodging resistance has been a major target of plant breeders as a means to protect yield in cereal crops. There has also been commercial focus on standing ability in field bean, pea crops and forage maize although little scientific evidence was found supporting this as a major breeding goal in these crops.
- Developing varieties that show resistance/tolerance to diseases has been shown to be a major driver of plant breeding efforts across all crops, with winter wheat and barley in particular showing resistance to a wide range of diseases.
- There is also work underway to further the scope of disease resistance across all crop groups, for example QTLs have been identified for resistance to verticillium wilt in oilseed rape and work is underway to develop suitable varieties for UK markets with resistance to powdery mildew, leaf and pod spot and pea seed borne mosaic virus (PSbMV) in peas, fusarium in forage maize and Beet Mild Yellowing Virus (BMV) and Beet Yellow Virus (BYV) in sugar beet.
- Resistance/tolerance to pests has received little commercial breeding focus across most crop groups. The main success in breeding for resistance to pests is the introduction of orange wheat blossom midge (OWBM) resistance into milling and feed wheat cultivars. Other successes include the introduction of the oilseed rape variety Amalie to the commercial market in 2014 with resistance to Turnip Yellowing Virus (TuYV) and the release of beet cyst nematode (BCN) resistant varieties of sugar beet on the BBRO Recommended List.
- Pre-commercialisation work is underway to develop varieties that are suited to UK conditions with specific resistance/tolerance to pests such as aphid resistance in cereal crops, stem nematode resistance in field beans and European corn borer resistance in forage maize.

- Crop varieties can help to control weeds through increased competitiveness and early vigour, however the role of plant breeders in weed control is more limited compared to the scope of breeders to aid control of diseases and pests.

#### 4.2.2 Increasing the efficiency with which inputs are used

A key objective of Sustainable Intensification is to improve resource use efficiency which is defined as '*using the Earth's limited resources in a sustainable manner while minimising impacts on the environment*' (EU Commission, 2014). Resource use efficiency in the context of plant breeding focuses on improving the efficiency with which the plant uses resources, principally water and nutrients. Improving resource use efficiency under low inputs is a goal of European research; the SOLIBAM project which ran between 2010-2014 aimed to identify specific traits or combinations of traits for adaptation to low-input/organic conditions over a wide range of different agro-climatic conditions in Europe and Africa (SOLIBAM, 2013).

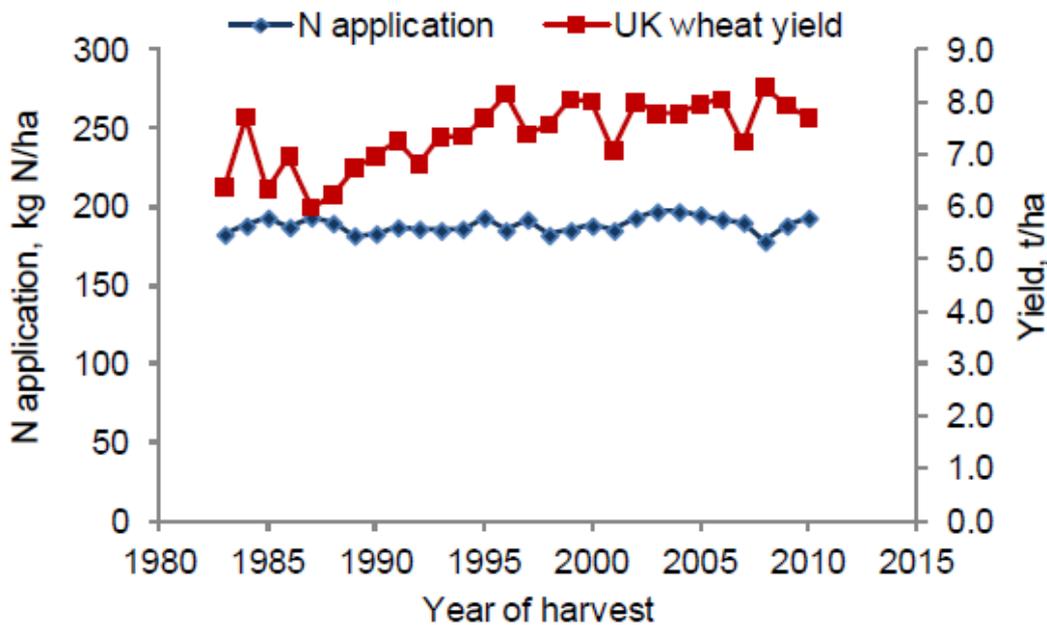
##### Nutrient use efficiency

Nutrient use efficiency targets improving plant use of key nutrients such as nitrogen and phosphorous. Research suggests that if N fertiliser requirement could be reduced by 20% the effect on N leaching would decrease by 15% and 46% per annum in winter wheat oilseed rape respectively and global warming potential (equivalent tonnes of CO<sub>2</sub>, GWP) arising from winter wheat production would decrease on average by 19% and for winter oilseed rape by 31% due to a reduction in denitrification and burning of fossil fuels for N fertiliser manufacture (Defra 2004a).

##### Wheat

Our review suggests that the yield trend in wheat over the last 20 years has led to an overall improvement in nutrient use efficiency as the higher yield has been attained with the same nitrogen input (Figure 8). However, not all findings concur; research from Defra's Indicator and Monitoring Framework suggests that from 2000 onwards there has been little increase in nitrogen use efficiency in wheat (Defra, 2014) and instead nutrient requirements, as defined by the economic optimum amount of nutrient fertiliser, have also increased. Findings from the GREEN grain project concur, suggesting that breeding for higher yields has led to increased N uptake efficiency but not increased N utilisation efficiency (Sylvester-Bradley *et al.*, 2010), although there is scope to improve this (Barraclough *et al.*, 2010).

To achieve more efficient use of nitrogen crops with high yields and low N optima (HYLO) traits are required (Sylvester-Bradley and Kindred 2009).



**Figure 8. Nitrogen application vs UK wheat yield**

Source: Knight *et al.*, (2012)

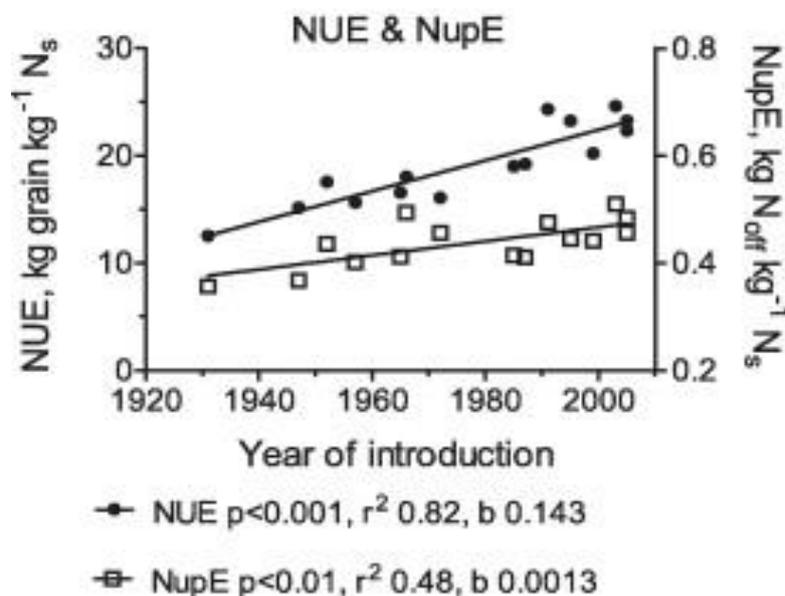
Further improvement to nitrogen use efficiency of wheat has been the focus of research by the European Commission via the NUE-CROPS project which ran between 2009-2014. There has also been some research carried out through the Wheat Breeding LINK programme to improve the performance and stability of performance of winter wheat under lower input environmental conditions using Composite Cross Populations (CCPs) which are populations of segregating individuals derived from inter-crossing a number of parents. Instead of selecting 'promising' individuals in each generation, the whole population is exposed to natural selection in each subsequent generation. The WGIN also aims to improve nitrogen use efficiency in wheat by targeting canopy longevity/rate of canopy N remobilisation and assessing variation in early N uptake as a contributor to seedling establishment and overall efficiency of nitrogen uptake, as well as determining whether functionality can be maintained at reduced grain protein. Genetically reducing the nitrogen emissions and growing costs of wheat production was also one of the objectives of the GREEN grain project which aimed to identify wheat genotypes with minimal nitrogen storage in the stems, and reduced gliadin protein in the grain. The project identified that there was sufficient genetic variation amongst elite and 'global' germplasm to breed varieties with the 'GREEN grain' ideotype - having both low canopy nitrogen and low grain protein, with certain varieties demonstrating desirable GREEN traits such as Defender (good N capture), Creativ (low leaf N), Solstice (low leaf sheath & stem N), Acropolis (low ear N), Exsept (low straw & chaff N), and Audi (low grain N) (Sylvester-Bradley *et al.*, 2010).

Genes linked to improving nitrogen use efficiency have been found, focusing on N-assimilation (e.g. nitrate reductase, nitrite reductase, glutamine-synthetase, glutamate-dehydrogenase), reduced plant size (e.g. Rht-B1, Rht-D1) and photoperiod sensitivity (e.g. Ppd-D1) (Berry *et al.*, 2011). Research by Shewry *et al.*, (2013) has also identified the highly N responsive gene,  $\gamma$ -gliadin which can be used in breeding programmes to reduce N fertiliser requirement.

Traits linked to nitrogen use efficiency differ between feed and milling wheats; in feed wheat, specific traits linked to increased nitrogen use efficiency include root length density at depth, capacity for N accumulation in the stem, low leaf lamina N concentration, more efficient post anthesis remobilisation of N from stems to grain, but less efficient remobilisation of N from leaves to grain and a reduced grain N concentration. In contrast to feed wheat, milling wheat varieties require a high leaf lamina N concentration to provide adequate grain nitrogen concentration, with other traits linked to nitrogen use efficiency focusing on high N absorption, high post-anthesis N remobilisation and increasing the proportion of grain protein as glutenin proteins to facilitate the maintenance of acceptable bread-making quality whilst reducing excessive N fertiliser inputs (Foulkes *et al.*, 2009). Other traits linked to improved nitrogen use efficiency include optimising late season rooting (Gregory *et al.*, 2005), heading date, thousand kernel weight and grain protein yield (Sylvester-Bradley *et al.*, 2010) and senescence date (Gaju *et al.*, 2011).

### Barley

Defra research suggests that over the last ten years there has been an upward trend in production per unit of applied manufactured nitrogen of winter and spring barley (Defra, 2014). Other research by Bingham *et al.*, (2012) concurs, highlighting that breeding over the last 75 years has increased the nitrogen use efficiency of spring barley as a result of an increase in N uptake and utilisation efficiency, with around a 1% increase in nitrogen use efficiency per year (Figure 9).



**Figure 9. Nitrogen use efficiency of spring barley varieties differing in date of commercial introduction**

Source: Bingham *et al.*, (2012).

There has been some research focusing on further improving nitrogen use efficiency in barley, with traits linked to nitrogen use efficiency identified and partial sequences of five genes related to N-metabolism in barley found, i.e. nitrate reductase 1, glutamine synthetase 2, ferredoxin-

dependent glutamate synthase, aspartate aminotransferase and asparaginase (Matthies *et al.*, 2013).

### Oats

Oats are considered to have a greater nitrogen use efficiency compared to other cereals, with the nitrogen uptake efficiency (NUpE) of oats suggested to be 67% which is 2% higher than in winter wheat and 4% higher than that of winter barley (Sylvester-Bradley and Kindred 2009). There has been little UK research conducted into increasing nutrient use efficiency in oats, although work by Griffiths *et al.*, cited in Marshall *et al.*, (2013) suggests that nitrogen use efficiency has increased over time. In Finland, the nitrogen use efficiency of spring oats increased between 1909-2002, although no clear differences in nitrogen use efficiency were found between modern spring oat varieties (Muurinen *et al.*, 2006).

### Oilseed rape

Nitrogen use efficiency has become an important target for oilseed rape (Vincourt, 2014) and oilseed rape has shown an overall upward trend in production per unit of applied manufactured nitrogen fertiliser over the last 10 years, although there has been little or no improvement in nitrogen use efficiency over the short term (2 years) (Defra, 2014). Traits linked to improved nitrogen use efficiency in oilseed rape have been identified (Berry *et al.*, 2011) and relate to higher N uptake until maturity, efficient N re-translocation and lower grain-N concentration (Koeslin-Findeklee *et al.*, 2014).

### Field beans and field peas

No evidence was found for this review to show there has been focus on improving nitrogen use efficiency in field beans or field pea crops.

### Herbage

Improving nutrient use efficiency of herbage crops has been an objective for plant breeders with research conducted through the LINK projects (LK0685, LK0686 and LK0687) funded under the Sustainable Livestock Production (SLP) LINK programme.

#### **Nitrogen use efficiency in herbage crops**

Plant breeders have aimed to improve the nitrogen use efficiency of perennial ryegrass in the rumen by developing perennial ryegrasses with increased dry matter digestibility and elevated levels of water soluble carbohydrates as part of LINK projects LK0686 and LK0687. LINK project LK0686 aimed to develop new varieties of perennial ryegrass with 10-15% higher nitrogen use efficiency than current varieties and developing new red clover varieties with a 15% enhancement in Polyphenol Oxidase (PPO) activity which has been linked to a reduction in both proteolysis and lipolysis, resulting in greater N use efficiency and protection of PUFA across the rumen (Defra, 2013c). This was successful, with clover lines developed with different levels of PPO activity and five perennial ryegrass populations with nitrogen use efficiency QTLs developed for National and Recommended List trials. LINK project LK0687 aimed to increase the efficiency of nitrogen use in the rumen via marker assisted selection based approaches to develop a range of perennial ryegrass varieties with water soluble carbohydrate levels (WSC) 8% beyond that commercially available and develop white clover varieties with 5-10% reduction in leaf protein content (Defra, 2013d). Again this was successful, with four ryegrass varieties entering into National and Recommended List trials which had enhanced WSC levels and a new clover variety,

Ac4835 showing a reduction in protein content compared to benchmark varieties which was entered into National List trials in England and Wales for sowing during 2013.

### Phosphorous use efficiency in herbage crops

Our review identified that improving phosphorus use efficiency has been a focus of plant breeders in herbage crops with LINK project LK0685 funded which aimed to develop productive varieties of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) with at least 10% higher intrinsic phosphorus use efficiencies than current varieties and incorporating these into genetic backgrounds with high agronomic performance (Defra, 2013b).

### Forage Maize

Our review found little evidence of focus on improving nutrient use efficiency in forage maize. Traits linked to nitrogen use efficiency have been identified and include anthesis-silking interval and leaf area duration (Gallais and Coque, 2006). Engineering nitrogen fixation ability into non-nitrogen fixing crops has been a long standing objective of plant breeders, with research carried out to better understand the N fixing ability of *Azospirillum spp*, the endophytic bacteria present in forage maize (Pisarska *et al.*, 2011).

### Sugar beet

Research from Defra suggests that output per unit of nitrogen applied has increased over the last ten years in sugar beet with a positive increase in nitrogen use efficiency also seen in the last two years (Defra, 2014).

### Water use efficiency

Water use efficiency (WUE) is fundamental to producing higher yields under low water availability or drought conditions. WUE can be improved via increasing the efficiency of light energy to biomass and improving depth of rooting (Spink *et al.*, 2009). Our research suggests that some progress has been made in enhancing rooting in wheat, with differences in rooting exploration at depth reported in wheat crops (Gregory *et al.*, 2004). Research is also underway (New Wheat Root Ideotypes LINK) to quantify the effect of nitrogen on wheat rooting with the aim to develop marker selection tools for plant breeders to improve rooting depth. The EUROOT project also aimed to improve water and nutrient use efficiency by mapping the cereal root system ideotype in terms of architecture, uptake and signalling processes to maintain crop performance under limited soil water and nutrients.

Research has also been undertaken to improve water use efficiency of perennial ryegrass varieties, with the *Festulolium loliaceum* amphiploid cultivar 'Prior' shown to be consistently effective at both soil water retention and reducing run-off (Humphreys *et al.*, 2005). Research has also been undertaken by LINK project LK0688 in herbage crops which focused on improving water use efficiency via enhancing rooting and aimed to develop new varieties of ryegrass and white clover for entry into National and Recommended List trials (Defra, 2013a). This was successful, with one variety (BB2540) which had 80% better water use efficiency than an Italian ryegrass/fescue control variety as well as improved sugars, yield and D value entering into National List testing in 2013 and another drought tolerant perennial ryegrass variety expected for entry into National list testing in 2016. Under LK0688, the drought tolerant clover variety -AX

17-also entered National list trials in 2013, with the target of breeding rhizomatous medium and large leafed, drought tolerant clover varieties in the future.

### Improving Resource Use Efficiency- Summary

- Research has focused on improving water use efficiency in wheat and forage crops via improving rooting such as the EUROOT project and the New Wheat Root Ideotypes LINK and LINK project LK0688 which aimed to develop forage varieties that can maintain crop performance under limited soil water and nutrients.
- Research has shown that the nitrogen use efficiency of barley, oilseed rape and sugar beet has increased over the last decade. The evidence of change in nitrogen use efficiency in wheat is conflicting, with Knight *et al.*, (2012) suggesting that increased yields have led to an increase in nitrogen use efficiency as a higher yield can be attained with the same input, whilst Defra research suggests that there has been little increase in nitrogen use efficiency in wheat since 2000 (Defra, 2014).
- Our research has shown that some progress has been made to identify low N optima traits across crop groups, with QTLs linked to nitrogen use efficiency identified in wheat, barley, oats, oilseed rape and forage maize and breeding targets such as optimising late season rooting (Gregory *et al.*, 2005), plant height, heading date, thousand kernel weight and grain protein yield (Sylvester-Bradley *et al.*, 2010) found. Genes linked to nitrogen use efficiency have also been identified.
- Our review has shown that there has been very little research focusing on improving phosphorous use efficiency in major arable crops, with the main research in this area conducted in forage crops via LK0685 project which aimed to develop perennial ryegrass and white clover varieties with higher intrinsic phosphorus use efficiency than currently available varieties (Defra, 2013b).

### 4.2.3 Reducing the negative environmental impacts of food production

Reducing the negative environmental effects of food production requires adapting to and mitigating against climate change, promoting soil health and maintaining or improving water quality. Plant breeders have a direct role in breeding crops that are adapted to varying environmental conditions and an indirect role in maintaining/improving soil health and water quality via improved crop varieties.

#### Adaption to environmental extremes

Reducing the negative environmental effects of food production requires adapting to and mitigating against climate change, promoting soil health and maintaining or improving water quality. Plant breeders have a direct role in breeding crops that are adapted to varying environmental conditions and an indirect role in maintaining/improving soil health and water quality via improved crop varieties.

Breeding crops that are adapted to changing environmental conditions is necessary for sustainable intensification of agriculture as climate change is likely to lead to an increase in

drought, salinity, heat and toxic heavy metals, with both genetic improvement and improved crop management needed to adapt to this threat (Royal Society, 2009). Plant breeders are considering the threat of climate change to crop production (Defra, 2012a), with some research suggesting that adaptation to climate change has started in northern Europe where there is evidence for overall spring advancement and phenology shift across the northern hemisphere of cereals (Peltonen-Sainio and Jauhiainen, 2014) which will require cultivars with a longer reproductive phases, lower photoperiod sensitivities (Martín *et al.*, 2014) and 'stay green' traits (Vignjevic *et al.*, 2015). A key component of adaptation to specific environments is developmental rate and flowering time, controlled in part by photoperiod response (*Ppd*) and earliness *per se* (*Eps*) genes, with the *Ppd*-1 variant *Ppd-A1a* identified as a potent novel source of photoperiod insensitivity for wheat breeding. Earliness *per se* (*Eps*) were also found to not have a negative effect on yield under UK conditions and could be used to provide alternative route to incrementally reduce flowering time for their target environments (Gosman *et al.*, 2014).

### Drought tolerance

Drought tolerance is the proportion of stress-free yield potential maintained when water is limiting (Ober, 2008). The UK is one of the world's most efficient producers of arable crops, yet approximately 30% of the current wheat area is grown on drought-prone land and drought losses are on average 1-2 t ha<sup>-1</sup>, which costs >£60M per year (Foulkes *et al.*, 2007). Drought tolerance is the focus of the European Research Project titled 'DROught-tolerant yielding Plants' (DROPS) which is due to finish in 2015. DROPS aims to analyse traits associated with tolerance to water deficit and water-use efficiency, identify genomic regions and genetic markers associated with these traits, assess the effects of marker alleles in different field drought situations in Europe and develop a model to test the effects of these alleles in maize and wheat.

### Wheat

Drought tolerance is the proportion of stress-free yield potential maintained when water is limiting (Ober, 2008). Globally, drought causes greater yield losses than any other single factor. It is estimated that as much as 50% of the wheat production area is regularly affected by drought. For example, the UK is one of the world's most efficient wheat producers, yet approximately 30% of the current wheat area is grown on drought-prone land where yield losses average 1-2 t/ha, costing growers >£60m per year. This means that even in years with 'normal' rainfall, potential yield and grain quality are affected by insufficient water at some time during crop development (Gosman *et al.*, 2014). Traits linked to drought tolerance have been identified (Khan *et al.*, 2007; Magyar-Tabori *et al.*, 2011; Ober *et al.*, 2005; Papaefthimiou and Tsafaris, 2012; Szira *et al.*, 2008). In wheat, research is underway to characterise rooting, with the wheat variety Shamrock, which has recent introgression of genetic material from wild emmer (*Triticum dicoccoides*), had significantly ( $p < 0.05$ ) greater root length densities at 60 cm and 70 cm depths compared to Shango and QTL were found for photosynthetic capacity and thermal time to senescence inherited from the recent wild emmer introgression (HGCA, 2014c). Genotypic differences in root characteristics have been found between wheat varieties (Ytting *et al.*, 2014), with high topsoil root length density, low tissue mass density, high specific root length, deep rooting and looser xylem vessels being associated with maximising soil water depletion (Nakhforoosh *et al.*, 2014) and physiological traits that contribute to drought tolerance during grain filling period found (Scotti-Campos *et al.*, 2015). It has also been shown that the progeny of wheat plants selected

for large roots have larger roots than their parents which could be used as a selection method in breeding programmes (Hermanska *et al.*, 2014).

### Barley

Drought tolerance has received some research investment in barley crops, with traits linked to drought resistance found e.g. high relative water content under stress (Szira *et al.*, 2008) and a gene (HvPKDM7-1) shown to be linked to control of drought tolerance in spring barley crops (Papaefthimiou and Tsiftaris, 2012).

### Oats

No evidence was found focusing on drought tolerance in oat crops.

### Oilseed rape

A review by Berry and Spink (2006) suggests that improving depth of rooting and improving branching should be a breeding focus to aid drought tolerance, but little evidence was found to suggest this has been a target of UK plant breeders.

### Field beans

Some research has been carried out focusing on improving drought and heat tolerance in field beans. Traits linked to drought tolerance have been identified, with stomatal conductance, leaf temperature and carbon isotope discrimination (Khan *et al.*, 2007).

### Field peas

Development of pea cultivars well adapted to dry conditions has been one of the major tasks of field pea breeding programs (Annicchiarico and Iannucci, 2008), with several morphological and biochemical traits linked to drought tolerance identified (Magyar-Tabori *et al.*, 2011) and QTLs have been identified and markers developed which can be used to select for individuals with desired drought adaptation in pea breeding programmes (Iglesias-Garcia *et al.*, 2015).

### Herbage

Plant breeders have aimed to improve drought tolerance in herbage crops. There have been some successes; in Italian ryegrass (*Lolium multiflorum*) an 88% improvement in yield has been demonstrated through the incorporation of selected drought resistance genes from related fescue species (Humphreys, 2005). Improving water use efficiency and drought tolerance were aims of the SuperGraSS project which demonstrated that a *Festulolium loliaceum* (*L. perenne* × *F. pratensis*) cultivar can reduce runoff by approximately 51% compared to *L. perenne* and 43% compared to *Festuca pratensis* due to initial intensive root growth followed by rapid senescence (BBSRC Responsive Mode Project, undated). The LINK project titled: Roots for the future- A systematic approach to root design: SUREROOT which runs from 2014-2018 aims to build on the SuperGraSS project to improve drought resistance and water use efficiency in clovers and grasses by altering root morphology. Research has shown that different grass species show drought tolerance traits to different degrees; *F. mairei* and *F. atlantigena* show good drought tolerance whilst *L. multiflorum* shows poor drought tolerance (Abberton *et al.*, 2011, Figure 10). In perennial ryegrass, variations in chlorophyll fluorescence were shown to be linked to differences in drought tolerance, with Amplified Fragment Length Polymorphisms (AFLP) identified as being prevalent in drought tolerant genotypes found which could provide a choice of selecting genotypes from this perennial ryegrass collection for a drought tolerance breeding program (Jonaviciene *et al.*, 2014).

Trait	L. p.	L. m.	F. p.	F. g.	F. a.	F. m.	F. atl.
Establishment	++++	+++++	+++	+	+++	+	++
Spring growth	++++	+++++	+++	++	+++	++	+++
Summer growth	+	++	+++	+++	++++	++	+++++
Digestibility	++++	+++++	+++	+	++	+	++
Winter hardiness	+++	+	+++++	+++	++++	++	+++
Drought resistance	++	+	+++	+++++	++++	+++++	+++++
Root depth	+++	++	++++	+++++	+++++	+++++	+++++
Persistency	+++	+	++++	+++	+++++	+++	+++++

**Figure 10 Sustainability traits in different herbage species. *L. perenne* (L.p), *L. multiflorum* (L.m), *F. pratensis* (F.p), *F. arundinacea* (F.a), *F. mairei* (F.m) and *F. atlantigena* (F.atl.). Trait expression (+) is poor and (++++++) is excellent**

Source: Abberton *et al.*, (2011)

### Forage Maize

Drought tolerance has been a target of European forage maize breeders, with drought susceptibility indexes (DSIGY) found to vary from 0.381 to 0.650 in modern maize varieties (Grzesiak *et al.*, 2013).

### Sugar beet

Drought is an important limitation to sugar beet production in the UK. Increased irrigation is not a viable answer to lack of rainfall and as such use of varieties with decreased sensitivity to water deficits is required (Ober *et al.*, 2005). In sugar beet, traits linked to root and sugar yield such as osmotic potential ( $\psi_s$ ), leaf area index (LAI), absorption of photosynthetic active radiation (PAR) and the efficiency of the photosynthetic apparatus ( $\Phi$  PSII) have been identified (Choluj *et al.*, 2014) and there is sufficient genetic diversity within the sugar beet germplasm to make breeding for drought tolerance a realistic breeding goal (Pidgeon *et al.*, 2006).

Traits linked to drought tolerance have been identified and include maintenance of green leaf area, droughted sugar yield and soil water extraction ability (Ober *et al.*, 2005). There has also been some focus on improving screening methods of drought tolerance, with carbon isotope discrimination proposed to be a useful tool in the genetic selection of drought tolerant sugar beet varieties (Rytter, 2005).

### Waterlogging tolerance

#### Wheat

Little work was found focusing on waterlogging tolerance as a specific breeding objective in wheat crops. However, by selecting for cultivars that are well adapted to UK conditions, it could be suggested that plant breeders have selected for the ability to compensate for waterlogging, where tolerance to waterlogging is a part of the general winter hardiness required to perform well in European climates (Dickin *et al.*, 2009).

## Other crops

No evidence was found in other crop groups studied related to waterlogging tolerance *per se*.

## Frost tolerance

### Wheat

Limited evidence was found in our review identifying frost tolerance *per se* as a specific breeding objective in wheat. Pre-commercialisation research demonstrates that frost tolerance does not appear to be negatively associated with other important agronomic and quality traits and is not associated with grain yield in durum wheat (Horst Longin *et al.*, 2013), showing that breeding for high yielding, frost tolerant varieties is possible.

### Field beans

Frost tolerance has been a focus of plant breeding in pulse crops, with traits linked to frost tolerance identified (Annicchiarico and Iannucci, 2007; Inci and Toker, 2011; Link *et al.*, 2010) and efforts underway to combine favourable alleles from frost tolerant accessions (Link *et al.*, 2010). In field beans, five frost tolerance QTL have been identified (Arbaoui *et al.*, 2007), with two clusters of QTL mapped on the linkage groups III and one cluster on linkage group VI linked to phenology, morphology, yield-related traits and frost tolerance in winter pea and two consistent frost tolerance QTL on linkage group V independent of phenology and morphology found (Klein *et al.*, 2014).

### Field peas

Some research was found focusing on developing field pea cultivars with frost tolerance. Traits linked to frost tolerance have been identified and include seedling height/number of leaves ratio (Annicchiarico and Iannucci, 2007). Photoperiod responsiveness has also been shown to influence frost tolerance, with the flowering locus *Hr* suspected to influence winter frost tolerance by delaying floral initiation until after the main winter freezing periods have passed (Lejeune-Henaut *et al.*, 2008).

## Other crops

No evidence was found focusing on breeding for frost tolerance in other crop groups studied in the UK or Europe.

## Soil health, biodiversity and protection

Soil health and biodiversity and minimising soil losses are fundamental aspects of sustainable production. Soil losses can arise via erosion through the action of wind and water and soil health can be damaged via compaction, urbanisation and industrial pollutants (Royal Society, 2009). Farm management practices are the main factor that affect soil quality and structure and are driven by regulation, market incentives, voluntary initiatives and farmer education. However, plant breeders can also have a role in improving soil health by increasing organic matter content of crops, increasing carbon sequestration, crops having a perennial growth pattern and improving rooting. The role of plant breeders in improving rooting in terms of resource use efficiency has been discussed above, although plant breeders have helped to reduce soil erosion through Defra Project IF0145 which focused on the role of genetic improvement with respect to 'environmental sustainability' traits in herbage crops by changing shoot and root architecture (Defra, 2013f).

## Water quality

Plant breeders can have an indirect effect on water quality via breeding for traits such as resistance/tolerance to diseases, pests and weeds and resource use efficiency which can help to reduce the amount of nutrient and plant protection products applied to crops, consequently reducing surface run-off into watercourses. An example of where plant breeding has helped improve water quality is through LINK project LK0973 which focused on reducing effects of diffuse pollution from pig and poultry units by developing and evaluating low phytate wheat germplasm (Defra, 2010a). LINK project LK0980 also aimed to reduce diffuse pollution of poultry operations by selecting wheat cultivars of high and consistent nutritional quality (Defra, 2009b). Results from LK0980 showed a positive relationship between apparent metabolisable energy (AME), dry matter digestibility (DMD) and N retention in wheat which could be useful in developing wheat cultivars of consistent nutritional quality in the future as DMD is less expensive to measure compared to AME and N retention (O'Neil and Wiseman, 2013).

## Summary- Reducing the negative environmental impacts of food production

- Drought tolerance has received the most research focus across the crops included in this review, with traits and QTLs linked to drought tolerance identified across most crop groups.
- Limited research has been carried out by plant breeders to select cereal or oilseed rape crops that show frost tolerant traits in the UK. Initial research has been carried out to select for frost tolerance in pulse crops; with traits and gene loci linked to frost tolerance identified (Link, Balko and Stoddard, 2010; Lejeune-Henaut *et al.*, 2008), however this research is at the pre-commercialisation stage with breeding progress in this area hampered by lack of sources of winter hardiness in pulse genetic stocks and perceived lack of market demand for this trait in commercial varieties.
- We found no evidence that waterlogging tolerance *per se* has been a specific objective of UK plant breeders. However, by breeding cultivars suited for EU and UK markets tested through National and Recommended List procedures it could be suggested that tolerance to typical levels of waterlogging has been delivered indirectly as part of the general winter hardiness required to perform well in European climates (Dickin, Benet and Wright, 2009).
- Plant breeders have an indirect role in protecting soil health and biodiversity via increasing organic matter content of crops, increasing carbon sequestration and improving rooting. Research has been undertaken to improve rooting in wheat e.g. SUREROOT and in herbage crops e.g. SuperGraSS in order to improve soil stability.
- Plant breeders have an indirect role in maintaining and improving water quality via breeding for traits such as resistance/tolerance to diseases, pests and weeds and resource use efficiency. Plant breeders have also specifically targeted improving water quality through LINK projects LK0980 and LK0973 which aimed to reduce diffuse pollution from pig and poultry units via selecting wheat cultivars of high and consistent nutritional quality (LK0980) and developing low phytate germplasm (LK0973).

#### 4.2.4 Maintenance of genetic resources and germplasm availability

Genetic variation in crops is fundamental to achieving higher yields whilst also protecting crop biodiversity (Defra, 2012b; Foresight Report, 2011). A major objective of modern breeding is to screen wild ancestors of crop plants, identify valuable 'left behind' alleles and introduce them into elite breeding material (Gosman *et al.*, 2014) to improve diversity. Some sources suggest that crop genetic diversity has declined steeply in recent decades, with a comparison of the relationships among all lines that have been on the UK barley Recommended Lists since 1990 showing that current spring barley varieties are much less diverse than those from the 1990s and early 2000s, although there is still considerable genetic variation that can be used to make further progress in barley breeding (Thomas *et al.*, 2014). However, other evidence suggests that genetic diversity has been maintained across most combinable crops (Chiapparino *et al.*, 2006; Martos *et al.*, 2005; Ordon *et al.*, 2005). For example in wheat, Orabi *et al.*, (2014) showed that modern plant breeding have succeeded in maintaining genetic diversity in modern wheat cultivars.

To contribute to the maintenance of genetic resources and germplasm availability, plant breeders have helped to maintain germplasm collections such as the John Innes Centre Germplasm Resource Unit, the Gediflux Collection (WISP, 2014) and the AE Watkins Collection which has a high level of genetic diversity (Wingen *et al.*, 2014). In addition, there are also dedicated industry programmes to enhance the diversity of the modern wheat gene pool such as the Wheat Improvement Strategic Programme (WISP) which is funded by the Biotechnology and Biological Sciences Research Council (BBSRC) between 2011 to 2017 and aims to produce new and novel wheat germplasm characterised for relevant traits and identify genetic markers for selecting these traits. In the UK, Defra has supported the maintenance and expansion of genetic diversity by funding the Wheat Genetic Improvement Network (WGIN), Oilseed Rape Genetic Improvement Network (OREGIN) and Pulse Crop Genetic Improvement Network (PCGIN) which aim to produce pre-breeding material needed to develop improved crop varieties.

#### Summary- Maintenance and improvement of genetic diversity

- Plant breeders have taken steps to preserve the genetic diversity within crop species by helping to maintain genetic collections such as the Germplasm Resource Unit, AE Watkins Collection, the Gediflux collection and the John Innes Pisum Collection.
- Plant breeders have also participated in research designed to maintain and improve the genetic diversity within crop species such as the Wheat Improvement Strategic Programme (2011-2017) funded by BBSRC which aims to broaden the pool of genetic variation in wheat.
- Plant breeders are also part of Defra funded initiatives to improve genetic diversity such as the Wheat Genetic Improvement Network (WGIN), Oilseed Rape Genetic Improvement network (OREGIN) and Pulse Crop Genetic Improvement Network (PCGIN).

## 5 Conclusion

- Plant breeding has met the definition of sustainable intensification by targeting raising yields across crop groups. This has helped to increase the efficiency with which inputs are

used through increasing output per unit input and targeting improved nutrient and water efficiency traits in crops which can lead to higher yields. By focusing on raising yields and improving resource use efficiency, plant breeders have also contributed to reducing the negative environmental impact of food production and improved water quality and soil stability.

- Our research suggests that the main emphasis of commercial plant breeding in the last ten years has been focused on enhancing and protecting yield in major arable crops, thereby driving greater production from the same amount of land, a key requirement of sustainable intensification. The focus on improving yield is dictated by market drivers; wheat and oilseed rape are the main arable crops grown in the UK and as such breeding efforts have been primarily directed to protecting yield in these crops, whilst increasing yield has been less of a breeding focus in minor crops such as pulses.
- Another main focus of plant breeding identified in our research has been developing crop varieties that meet specific end user requirements in crops such as in cereals and oilseed rape, thereby reducing waste in the supply chain by improving processing efficiency. Our research also showed that plant breeders have aimed to reduce anti-nutritional factors in crops such as oilseed rape, pulses and oats which can help to maximise use and improve efficiency when used in livestock diets.
- Disease resistance has been a major target of plant breeders over the last ten years. Wheat and barley crops show resistance to a wide range of diseases, whilst resistance to diseases in oats, pulses and forage maize is more limited and dictated by market drivers. Herbage crops show resistance to a wide range of diseases as shown by the Grass and Clover Recommended List 2014, although little scientific evidence was found highlighting that disease resistance was a major breeding target in these crops; with yield stability and quality traits the main breeding drivers. There has also been success in breeding for AYPR resistance in sugar beet due to the use of double resistance genes Rz1 and Rz2.
- Pest resistance/tolerance has received little research focus in the past due to lack of financial incentive for breeders to target this trait and the fact that insecticides are relatively cheap and are thus widely used against pests. This has started to be addressed in wheat through initiatives such as the Wheat Genetic Improvement Network (WGIN) and the release of commercial oilseed rape and sugar beet varieties that show pest tolerance traits, although much of the work that has been done in this area is at the pre-commercialisation stage.
- Weed resistance/tolerance has also received little breeding focus, with chemical or cultural measures the main method of control. Weeds can potentially cause greater yield losses than from pests or diseases, and with herbicide resistant black-grass increasing in the UK, tolerance of weeds is a key priority. Although it is unlikely that plant breeding will be able to make significant progress to advance this enough to replace effective herbicides and cultural control options, it could play an important additional role.

- Resource use efficiency *per se* has been a lesser breeding goal, with most research into this area at the pre-commercialisation stage. By increasing yield at an unchanged level of nitrogen applied the nitrogen use efficiency of most crops has increased over time, but further work is needed to specifically target N use efficiency traits across all crop groups and to improve this even further.
- Plant breeders have developed crops suited to different climates using diverse locations of breeding stations to develop varieties specifically adapted to particular conditions. Good progress has been made in selecting for drought tolerance traits in wheat and herbage crops, mainly by improving breeding, but there is scope to widen this research to other crops.
- There are elements of sustainable intensification where the role of plant breeding is likely to be more limited. These include maintaining and/or improving soil health and water quality, where legislation and farm management practices are key drivers of impact. However, plant breeders do have the opportunity to indirectly make improvements to soil health and water quality via improving rooting, with research underway to address this mainly in wheat and herbage crops. Resource use efficiency also has the potential to improve water quality by reducing the amount of inputs needed to achieve a desired yield. Research aimed at producing cultivars that reduce the need for inputs which are key concerns over water quality, such as nutrients, and some specific molluscicides and herbicides could help in future.
- Maintaining genetic diversity is required to select for traits that enable a crop to be well adapted to current and future environmental conditions. This has largely been achieved by plant breeders through contributions to, and maintenance of, germplasm collections such as the Germplasm Resources Unit and participation in government and industry funded initiatives.

In summary, plant breeders have had, and will continue to have, a key role in the sustainable intensification of modern agriculture through balancing yield increases with environmental objectives. Plant breeding has delivered on many objectives of sustainability and sustainable intensification through having yield as a major focus. There is evidence that these impacts have been delivered to the market place through traits such as yield improvements, disease resistance and crop quality. Further work is in progress with a view to developing commercial varieties which deliver pest resistance and further improved nutrient use efficiency.

## 6 Summary of impact of plant breeding in targeting specified traits

A summary of the objectives of plant breeding across crop groups is shown in Figure 11. Blue coloured boxes denote where we found evidence for traits which have already had an impact in the market place due to the efforts of plant breeders, although ongoing work is required in these

areas to keep developing improved varieties that meet sustainability goals in the future and to address other specific issues. The green boxes relate to areas of plant breeding where we found that work is in the breeding pipeline or where little work has currently been carried out in this area and further research investment either from public funding or public/private funding collaborations is needed. The text in the boxes gives illustrative examples only of work in this area and is not meant to represent all the work carried out in these areas.

Trait	Wheat	Barley	Oats	Oilseed rape	Field Beans	Field Peas	Forage Maize	Herbage	Sugar beet
Increase harvestable yield	Increase by 0.7t/ha decade since 1980	92% increase in W.B & 87% in S.B since 1982	Improve harvest index and no. grain per sq. metre	0.5t/ha increase per decade since 1980	Little increase seen in last 10 years	Little increase seen in last 10 years	Focus on DM and starch yield	Focus on DM yield	Faster increase than any UK arable crop since 1980
End use quality	Bread making quality	Low $\beta$ -glucan levels, low $\beta$ -amylase	Naked oats, oil content	Decrease glucosinolate & fibre	Reduce tannins, amino acid content		Digestibility, energy content	Sugar content	
Resistance to disease	Eyespot, Sept., rust	Mildew, rust, Rhyncho. Ramularia, Net blotch	Rust, mildew	LLS, stem canker	Leaf and pod spot	Pea wilt, Downy mildew	Eyespot	Mildew, Rhyncho. rust	AYPR
				Verticillium, alternaria	Ascochyta blight, rust	P. mildew, Ascochyta	Fusarium		BMYV, BYV
Resistance to pests	OWBM	Little work	Little work	TuYV	Stem nematode resistance	Little work carried out	Corn borer resistance	Little work	BCN tolerance
	Aphid, BYDV								
Adaption to env. extremes	Drought traits identified	Little work	Little work	Little work	Traits identified	Traits identified	QTLs found	Drought tolerant	Traits identified

Impact in market place

Work in progress/development required

Figure 11. Examples of the impact plant breeding has had on specified traits in major arable crops

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