Using genetic resistance to combat pest and disease threats

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Summary

Wheat diseases and pests account for a high degree of grain losses and quality degradation in the UK to an extent varying from year to year according to the particular threats in any year. As climate change is expected to continue to occur in the future, threats from both known and new diseases and pests are likely to increase. This factor, combined with resistance to current fungicides and the current obstacles to new pesticide product registration, will intensify the need for plant breeding to provide major genetic solutions to the control of diseases and pests. The combination of genetic resistance and chemistry will provide growers and end users with opportunities to maximise grain production and enhance grain quality as well as producing wheat in a sustainable manner.

Introduction

The high value of disease resistance was never doubted prior to the development of effective fungicides in the early 1970s. Without fungicides, varieties were at risk from fungal infections with potentially harmful consequences in terms of food supply and potentially damaging mycotoxin production. Following the introduction of very effective fungicides, growers and the testing authorities saw different priorities, with grain yield being the primary driver in terms of variety choice. Growers also changed their approach to drilling wheat by sowing earlier than before and as a consequence the disease threat increased. With buoyant grain prices and effective fungicides, the variety profile changed dramatically - to be dominated by varieties with poor disease profiles but with very high yield potential when treated prophylactically with fungicides.

Currently, high grain prices are increasing the incentives for intensive wheat growing. In contrast to the 1970s, growers now have to respond to new pressures: insensitivity to both older and newer fungicides as well as the need to grow wheat in a sustainable manner with due regard to the environmental consequences. The value of genetic resistance is now under greater scrutiny than any time since the early 1970s but breeders are better placed to meet these challenges. In addition to the increased awareness of the genetics of disease resistance, plant breeders now have access to a range of technologies to map genes and follow their inheritance through breeding programmes. Breeders have also developed the means of accelerating material through the plant breeding 'pipeline' to meet challenges as they appear.

There is an equilibrium between chemical and genetic control of diseases and pests and this can be compared to a pendulum whereby the balance varies according to a number of issues – primarily economic, climatic, grain price and disease vulnerability of the variety being grown. In reality a complete genetic solution for controlling many diseases and pests is unlikely to be an option and growing wheat in the UK will continue to use a balance between genetic resistance and chemical control. Whilst the UK provides growers with one of the best environments in the world to produce grain, it also provides an ideal environment for diseases and pests.

The potential for exploiting genetic resistance to diseases

Wheat may be threatened by a range of root and foliar diseases. There are high levels of resistance to nearly all of the diseases prevalent in the UK but the basis of the genetic resistance varies according to disease. Table 1 illustrates the potential for disease resistance breeding.

Table 1. Genetic variability for disease resistance and prospects for improvement

Disease	Available genetic resistance
Mildew	Immunity
Yellow rust	Immunity
Brown rust	Immunity
Septoria nodorum	Very high
Septoria tritici	Very high
Eyespot	Near immunity
Fusarium	High
Take all	Poor

A significant disease threat is 'take all' *(Gaeumannomyces graminis* var. *tritici)* for which at present only poor resistance is available in wheat. This problem must, in the longer term, be seen as a target for genetic modification (GM) technology.

Breeding strategies for disease resistance breeding

The four following examples illustrate how breeders are managing various disease threats with particular reference to the role that new technologies now play in delivering more robust and sustainable resistance in varieties.

Yellow rust (*Puccinia striiformis*)

Yellow rust is endemic within the UK with many growers only too aware of the dangers posed. The disease came to prominence with the devastating outbreaks in 1966 on the wheat variety Rothwell Perdix which caused severe yield losses. The appearance of this new and destructive race provided the motivation for new cereal pathology work to gain a better understanding of race populations and the breeding of varieties with thoroughly tested genetic resistance. In 1967, the UK Cereal Pathogen Virulence Survey (UKCPVS) was set up, primarily to detect changes in virulence in important diseases and determine the significance of these for commercial varieties and breeding programmes, work which still continues with HGCA funding. At around the time that UKCPVS was started, Nickerson began to employ leading cereal pathologists to support breeders in its quest for new, diverse and potentially 'safer' resistance factors.

Since the yellow rust outbreak on Rothwell Perdix, periodically new and important yellow rust virulences have continued to appear overcoming resistance in varieties such as Joss Cambier, Slejpner, Brigadier and Robigus.

Breeding for resistance to yellow rust has been based upon the exploitation of major genes and to responding to the consequential breakdown of resistance as the pathogen mutates to overcome resistance. Combinations of major genes which, individually, have already been 'matched' by the pathogen can provide another level of resistance but this too is potentially susceptible to breakdown and invariably short-lived. Combinations of partial resistances, which tend to have durability, are now considered to be safer options. However, understanding and working with such resistance requires a deeper knowledge of the genetic basis of the resistance. Breeders are now mapping the major genes involved and identifying varieties with known combinations. This gives the breeder the opportunity to define the risk associated with any known combination in varieties under test. In addition the use of molecular markers to tease apart the contributions of *partial resistances* now provides an extremely useful tool for overcoming the threat of this disease. Longer term robust resistance based upon the 'stacking' of different sources with a proven level of durability must be the best solution. The effects of moderate resistances can be additive and combined to provide near immunity.

Table 2. The most widely used resistance genes, their date of introduction into the UK and the associated change of NIAB/ CEL disease ratings

Year virulence appeared	Variety	Resistance genes	Rating 'before'	Rating 'after'
1966	Rothwell Perdix	**Yr1** (Yr2,Yr6?)	1964 **9**	Removed from 1967 RL
1971/2	Joss Cambier	Yr2, (Yr3?),**Yr11**	1971 **6**	1972 **3**
1983	Stetson	**Yr1, Yr9**	1983 **9**	1984 **8[2]**
1985	Slejpner	**Yr9 + Yr??**	1986 **9[5]**	1989 **2**
1988	Hornet	Yr2, **Yr6, Yr9**	1988 **9**	1989 **(2)**
1988	Brock	**Yr7, Yr14**	1988 **7**	1989 **4**
1995	Brigadier	Yr9, **Yr17**	1995 **9**	1997 **2**
2000	Robigus	**YrRob**	2000 **8**	2007 **3**
2007→	'Alien Derivatives'	New, unknown	High	Low

Note: 'before' and 'after' refer to the development of yellow rust races virulent for that resistance gene(s)

A range of fungicides is available which can control yellow rust. In addition, seed treatments can delay disease development in the field. Baytan (triadimenol/ fuberidazole) continues to be popular, although it can delay emergence. New chemistry, available in Epona and Jockey/ Galmano (fluquinconazole + prochloraz), provides options for reducing the risk of growing susceptible varieties. It seems likely that fungicidal control measures, albeit sometimes to be used as a last resort, will continue to be available in the future for this major disease. This contrasts with the uncertainty that is now evident for the control of *Septoria tritici*.

Septoria tritici

This disease, almost unheard of prior to the late 1970s in the UK, is by far the most damaging foliar disease with even low levels resulting in significant yield losses. As such, it is a major breeding target for UK wheat breeders. *Septoria tritici* is primarily a disease of wetter areas of the UK but even crops in the drier eastern areas are vulnerable. Disease prevalence has arisen from the widespread growing of susceptible varieties such as Longbow, starting in the mid 1970s. The maintenance of high levels of inoculum was exacerbated by movement towards earlier sowing and the release of susceptible, but very successful, varieties such as Riband followed by Consort. Fuelled by high grain prices growers had little incentive to adopt varieties with higher levels of resistance but with lower yield potential. Breeders met the demands of growers by releasing more varieties with only modest levels of resistance.

It was clear in breeding programmes that higher levels of resistance were available and the release of the variety Claire in 1999 set new standards for resistance to *Septoria tritici*. This higher level of resistance was derived from two moderately resistant parents Flame and Wasp. Following on from Claire was the first variety with very high levels of resistance – Exsept – again derived from parents with moderate levels of resistance (Moulin, Boxer and Hereward). Despite failing to make Recommended List status this variety has been a major success with growers in high risk situations (early sowing and in the wetter areas of the UK) taking advantage of its excellent disease profile.

Resistance to *Septoria tritici* has been derived by combining partial resistance genes from a range of varieties. Higher levels of resistance still appear to be available in newer varieties in the breeding 'pipeline' from a range of breeders. The evolution of higher levels of resistance can be witnessed in the profile of varieties released by Nickerson-Advanta over the past ten years. Claire established a new level of resistance which has been superseded by Alchemy. and more recently by Lear, now in CEL Recommended List trials which sets a level similar to that found in Exsept but with a significantly higher yield potential. In contrast with yellow rust, resistance of this type has proven to be robust and despite press reports to the contrary, there is no evidence of significant reduction in resistance ratings.

The use of new technologies to increase the efficiency of selection tracking resistance, which can be based on specific or partial resistance, has proved to be complex. In order to apply more resources to understanding the genetics of resistance a number of breeders (Nickerson, Advanta, Elsoms, Syngenta, Sejet and Svalöf Weibull) have combined to tackle the problem. This collaboration has set a precedent for working together (mainly under the Defra-sponsored LINK programme) to tackle complex disease threats. Significant effects of some major genes have been detected but to date field selection has proved to be the most cost effective and resilient solution. In the longer term, breeders will continue to work with the public sector to determine which gene complexes need to be conserved.

Work with yellow rust and *Septoria tritici* has given breeders an insight into the potential threats and how new technologies can now be used selectively to provide varieties which will continue to be disease resistant in the longer term.

Eyespot (*Oculimacula* spp.)
The most damaging root disease in the UK (apart from the intractable problem of take-all) is eyespot (*Oculimacula* spp.). This endemic disease reduces yield and grain quality but is greatly underestimated by farmers.

In contrast to the situation with most foliar diseases, chemical control measures are not fully effective. For many years MBC-based fungicides gave good control until the fungus became resistant. Later products such as Unix (cyprodinil) and more recently Tracker (epoxiconazole + boscalid) and Proline (prothioconazole) have given growers more choice but control is not complete. Genetic resistance mirrors that of the chemistry – giving good levels of resistance but being incomplete. Again the combination of fungicidal control and genetic resistance must be seen as the route forward.

The genetic control of eyespot *Oculimacula yallundae* (W type), *Oculimacula acuformis* (R type) is now becoming clear. Most of the parental breeding material for resistance to this damaging disease originates from France, yet French varieties in general carry low levels of resistance – a reflection of the different agronomic practices prevalent within the country. In the UK growers drill earlier than their French counterparts and more second/ continuous wheats are grown; thus the need for resistance to eyespot is high.

The French variety, Cappelle Desprez, is the source of resistance to eyespot in most UK varieties. This resistance, introduced in 1946, still provides a moderately good level of resistance today. Resistance is based upon a single gene, named Pch2, located on chromosome 7AL and is now widespread amongst UK varieties. The inheritance can be traced through key varieties such as Professor Marchal, Norman, Galahad and Haven. Breeders recognise the value of this resistance and optimise selection for it using primarily field-based selection techniques – early sowing and sowing candidate varieties in second wheat situations. The resistance is however easily lost and without good screening of exotic germplasm within a breeding programme loss of resistance is likely.

The American, Roderick Sprague identified very high levels of resistance to this disease in the wild oat grass *Aegilops ventricosa* (bulbed oatgrass – a noxious weed in the US) in 1936. Resistance was transferred by French workers in the 1960s producing a breeding line VPM1 (VPM = *Aegilops* ***v****entricosa/Triticum* ***p****ersicum*//3***M**arne = ***V****entricosa* x ***P****ersicum* x ***M****arne*). Work at the Plant Breeding Institute, Cambridge transferred this to the first variety to carry very high levels of resistance to eyespot – Rendezvous. Though this variety only had modest success it became the parental material for more varieties with high levels of resistance within newer varieties such as Hyperion and Batallion. It was recognised that the resistance was simply inherited and associated with a single major gene designated Pch1.

Work at the John Innes Centre identified an isozyme marker closely linked to this gene and now the use of iso-electric focusing to track the resistance is routine in most UK wheat programmes. The science has however moved on and molecular markers are now also employed for this trait. As yet no confirmed marker for the Cappelle resistance has been identified but once this has been done the combination of Pch1 and Pch2 can be used routinely. Early concerns about reduced yield levels associated with Pch1 are being resolved as higher yielding parental material is being used in programmes. It is not clear how effective this combination will be in very high risk situations and how this genetic resistance should be used in conjunction with accepted chemical control. Work still needs to be carried out on how this resistance could be used in combination with both foliar sprays and targeted seed treatments to minimise lower yields in the demanding second wheat farm situation.

Breeding strategies for pest resistance breeding

UK breeders have highlighted the threat of insect pests (wheat orange blossom midge, yellow blossom midge, bulb fly, gout fly, aphids as vectors for BYDV etc) as key research targets. In addition to climate change, a major driver has been to reduce the use of insecticides. Enthusiasm for research has been encouraged by the development of varieties resistant to wheat orange blossom midge (*Sitodiplosis mosellana*).

Wheat orange blossom midge

This pest, previously accepted as sporadic, has become endemic across the UK with few years when there are not outbreaks, either regional or national. Work carried out by a consortium of breeders and academic parties under the Defra sponsored LINK programme identified a number of varieties resistant to this problematic pest.

Wheat orange blossom midge is an opportunistic pest – laying eggs into the florets of wheat when conditions are suitable. This makes control difficult and to date the most effective control measure has been the targeted use of chlorpyrifos. Varieties found to be resistant to wheat orange blossom midge have been identified which produce an 'antibiotic' reaction thereby killing any developing larvae from eggs laid within the florets. In many ways this is a 'near perfect' example of biological control as all varieties appear to be attractive to wheat orange blossom midge. Any eggs laid on resistant cultivars are 'wasted', thereby reducing the potential threat of future attack.

Pest incidence is sporadic giving breeders a problem in selection as without the incidence of attack varietal variation cannot be screened. This is a clear target for molecular markers. Segregating populations have been screened within the Nickerson-Advanta programme and markers have been identified which associate with this particular resistance. Screening is now carried out routinely within the programme and it is notable that competitor companies are following the same strategy. There appears to be no reason why the UK wheat acreage should not be converted into varieties carrying resistance to wheat orange blossom midge. However, breeders are also aware of the threat of using single major sources of resistance and are actively screening a wider range of germplasm for novel sources of resistance to this pest.

One of the major threats of this pest, apart from significant yield losses, is the associated loss of quality. Priority has been give to developing varieties with high quality and resistance to wheat orange blossom midge resistance. The first variety to come from this positive screening strategy, now in CEL Recommended List trials, is QPlus – a product of the cross Solstice (OBM susceptible) x Robigus (OBM resistant)

Future prospects

This millennium will provide enormous challenges for growers and consequently plant breeders as the need to provide food for growing populations in an environmentally wise way continues to increase. Historically, plant breeders have tended to take steps forward one at a time. The development of new technology – primarily the use of molecular markers – will allow breeders to 'pyramid' traits together. The examples within this paper illustrate the opportunity to combine high levels of disease and pest resistance. There are other constraints, of course, but already the base germplasm has been developed. The UK has a range of genetic material available to provide UK growers and consumers with the quality requirements in new varieties. In addition, material is now 'genotyped' as routine so that breeders are more aware of the potential for new combinations and the associated risks therein.

The role of the plant breeder has always been to predict variety requirements ten or fifteen years ahead. This presents quite a challenge and one only increased by uncertainty about predicted effects of climate change. Plant breeders are increasingly using sophisticated modern technologies to help them achieve their objectives with particular respect to diseases and pests. However because the UK environment is one in which diseases and pests thrive, growers will continue to use agrochemical inputs, albeit more selectively than at present.

In some areas of disease and pest control there may be a deficiency of genetic resources which can be exploited. In these, genetic modification (GM) technology may be the only long-term and sustainable option.

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