RESEARCH TOPIC REVIEW: Cereal variety and population selection

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1. Scope and Objectives of the Research Topic Review:

Breeding, with a particular emphasis on cereals, over the last half century has resulted in significant improvements in overall production (Murphy *et al.*, 2008). The increases in yield have largely been achieved by an improvement in the agronomic conditions, and a corresponding adaptation of varieties to those conditions (e.g. Ceccarelli, 1996). However these developments take place in line with the rise of oil-based inputs in agriculture and organic farmers are largely constrained to the use of these cereal varieties that have been bred for conventional production systems.

Conventionally bred varieties only achieve optimal performance with a myriad of inputs that are prohibited in organic systems. Significant yield and quality deficits in low input and organic growing systems result from the additional demands placed on these conventionally bred varieties. These include significant variations in soil nutrient status and weed, pest and disease pressure, within seasons, among sites and among variety on organic farms that cannot be ameliorated in the short term with the application of agrochemicals. There have been differences, however, in the amount of breeding effort and levels of agrochemical inputs used whilst breeding among different cereal species. Oats, for example, have been bred under lower input regimes than wheat and as a result yield relatively better than wheat under organic compared to conventional conditions.

To compound the difficulties of variety performance, organic farmers experience major variation in yield and quality between years. This is supported by a three year Defra funded study led by The Organic Research Centre – Elm Farm (OF0330) that evaluated the performance of three winter wheat varieties and their 3-way mixture on 18 farms across the country. The research demonstrated there was no statistical basis for selection of one variety over the other in organic systems. In other words, no particular variety was better suited than the others to the organic growing systems of all 18 farmers across the East to the West of the UK.

The major challenge to address is how to select and breed varieties suitable for low input and organic production. This review will describe variety characteristics suitable for organic conditions, approaches to cereal breeding for organic systems, and finally the scope for the future.

2. Summary of Research Projects and the Results

Plant characteristics

Plant characteristics will obviously vary enormously among cereal species and so will have a bearing on crop choice along with factors such as rotation and the intended market. There is also much variation within species which can be exploited during the breeding process. Wheat, for example, is an enormously adaptable crop. Its success relates to hexaploidy (having six sets of chromosomes: AABBDD) where the multiples of genetic material provide improved plant vigour and overall ability to buffer climatic variation.

Within this context, cereal phenotypes that are suitable for organic systems can be selected. These include: the physiologically efficient use of a wide range of nutrients and water; disease and pest resistance; good competitive ability against weeds; quality; and yield and yield stability.

Nutrient use efficiency

The nutrient availability in organic soils is dependent upon the mineralization of organic matter which is supplied from either a fertility building ley or from manures. In contrast to non-organic systems, high concentrations of available nutrients can be rarely achieved predominantly at the peak crop demand. Instead, nutrient release is dependent upon the temperature and biological activity of the soil and its interaction with the residues from a leguminous fertility building crop and/or farmyard manure (FYM). As a consequence, relatively accurate management of the nutrients in organic rotations is difficult to achieve. Varieties that are better suited to the nutritional regime of organic conditions are those that are capable of early season nutrient uptake, particularly of nitrogen (N), followed by the internal translocation at the point of, or before, grain filling (Baresel *et al*., 2007; Kitchey *et al.*, 2007). High early nutrient uptake enables the crop to take advantage of the nutrients that are rapidly released following the incorporation and subsequent mineralisation of fertility building leys. The varieties that stay green longer, i.e. those with delayed senescence, were found to have a higher protein content (Kitchey *et a.l*, 2007).

Assessments of old and more modern barley varieties has, to date, demonstrated that there is significant variation in the nutrient use efficiency (NUE) (the ratio of grain dry weight to nutrient supplied). Varieties were found to vary in not only the relative uptake of nutrients supplied but also the biomass produced per unit of nutrient applied (Baddeley *et al.*, 2007). Despite significant variation between varieties, there is little evidence to demonstrate that the modern breeding approach is selecting for improved NUE in cereals (Le Gouis *et al*., 2001, Baddeley *et al.*, 2007).

In wheat, an extensive evaluation of a range of cultivars over 11 seasons revealed that the more modern varieties are better adapted to exploiting large volumes of mineral nitrogen (Foulkes *et al*., 1998). The difference in plant nitrogen uptake in these modern varieties was suggested to relate to variety growth habit. Newer varieties with a lower number of tillers, but with greater longevity were suggested to have a delayed peak N demand that had to be satisfied by mineral fertilisers (Foulkes *et al*., 1998).

The dynamic nature of roots has been demonstrated by studies on a range of varieties of winter wheat and winter and spring barley (Gahoonia *et al.*, 2004). Under conditions of phosphorus (P) fertilisation, root hairs were shorter, and under such conditions there was little detectable difference in the P uptake of the different cultivars. The authors suggest that, as a result of the strong correlation between root hair length and P uptake in barley, root hair length is a suitable selection characteristic under conditions of low P.

The interaction between the cereal roots and various soil borne microbes could potentially elicit advantages to the crop including improved disease and nutrient management, drought resistance and tolerance to heavy metals (Gosling *et al.*, 2006). The pseudomonads are one such group of microbes; some strains of this bacteria produce antimicrobial compounds suitable for disease suppression, and it has been demonstrated that different wheat varieties accumulated various *Pseudomonas* spp. at differing levels (Lutz *et al.*, 2007). The root associating fungi, the mycorrhizae, have the potential to increase nutrient supply to the crop, particularly P, in exchange for crop-produced carbohydrates. Mycorrhizal associations also have the potential to increase the supply of other nutrients and improve disease resistance and soil structure. The mycorrhizae contain a wide range of species with different host and environmental adaptations. As a result, a precise evaluation of the importance of mycorrhizae in cereal production is difficult to achieve although it is generally recognised that organic systems are more favourable to the fungi than the non-organic equivalent. Mineral fertiliser application and the use of biocides can inhibit mycorrhizal growth and root colonisation, whereas FYM and composts do not have such a detrimental effect (although copper is damaging) (Gosling *et al.*, 2006).

Root structure and the consequent nutrient uptake are not only influenced by varietal differences but also by agronomy. The effect of drilling technique on root length density is being tested in a study led by the Organic Research Centre – Elm Farm (LK0970). Trials running at present have revealed that strip drilling with a Claydon Yieldometer drill may enhance total protein yield. Soil cores taken from strip and narrow row drilled plots will be compared to isolate any possible differences in root structure.

An alternative approach to improve the nutrient dynamics in organic cereals is being investigated in a project led by the University of Newcastle (LK0960). The application of chicken manure pellets at anthesis alongside different FYM and compost regimes are being trialled to determine whether there is improved synchrony between nutrient mineralisation in the soil and peak crop demand. No results have been reported to date that demonstrate a significant effect of the different fertiliser regimes on grain quality.

On most organic farms which do not use any inputs (compost, FYM, or rock phosphate), there is a P deficit. However, with the use of inputs, the management of P is dependent upon the soil characteristics and crop demand. The PLINK project (LK0963), led by The Scottish Agricultural College, is focusing on how to best manage rock phosphate inputs in organic rotations.

For organic systems, improved nutrient management can be achieved by selecting varieties with:

- early season N uptake followed by internal translocation of N at grain filling;
- higher nutrient use efficiency;
- a higher number of tillers;
- longer, and a greater number of root hairs;
- beneficial microbial associations;
- delayed senescence.

And adopting agronomy which:

- favours more extensive root systems; and
- improves management of composts, manure and rock phosphate.

Disease resistance

Plant nutrient status, crop rotation and the difference in the architecture of the organic crop stand have all been identified as reasons why the disease dynamics in organic crops are quite different to those recorded in equivalent crops under high input conditions. Diseases that are important in high-input systems compared to organic systems are those that are more influenced by plant nutrition, sowing density and time, and include powdery mildew, rusts, *Septoria tritici*, blotch and foot rot (Wolfe *et al.*, 2008). Although rusts and mildews are scored in organic trials in the UK, they occur later in the season with a consequent lesser effect on yield. In addition, seed borne diseases such as Fusarium head blight (FHB) are of major importance, as a result of the influence on food quality.

Fusarium head blight is caused by a combination of *Fusarium* spp. (including *Fusarium graminearum* and *F. culmorum*). The ear infections are usually most severe when flowering coincides with warm, wet conditions, such as those experienced in the UK in the summer of 2007. However, the additional factors of minimum tillage and susceptible pre-cropping significantly contribute to grain mycotoxin levels (Edwards, 2004). All cereals have some susceptibility to FHB, although the most susceptible cereal species and varieties vary between countries; a likely consequence of different climates, agronomy and resistance in the national cereal varieties (Edwards, 2004).

Fusarium infections in cereal can be more severe following application of mineral N fertilisers (Martin *et al.*, 1991); Edwards (2004) suggests this may be the result of changes in canopy structure and or physiological plant stress. Recordings to date have demonstrated that mycotoxins are, on average, lower in organic grain compared to grain from high input systems, and this trend is likely to continue as a result of the rotation, and lack of minimum tillage (OF0330).

Resistance to FHB has been identified in red hard wheat, but not in any of the other wheat classes. Although breeding is taking place to attempt to incorporate this resistance into new varieties of feed and milling wheat, there are none commercially available to date. This is mainly because of the difficulty of integrating the resistance into the new lines, whilst maintaining processing quality. Of the existing wheat varieties on the market, those that are tall, awnless and have a reduced ear density have a tendency to have less disease. All these characteristics act to reduce the moisture content in the microclimate around the developing ear, thereby creating conditions less favourable to fungal infection (Yuen & Schoneweis, 2008).

The microclimate within a cropping stand is also influenced by weed and/or inter-crops at the lower levels. Higher moisture levels have been shown to increase the incidence of stem diseases such as *Pseudocercosporella herpetrichoides* (Bennett & Cooke, 2006). It would be expected under these same conditions that spore dispersal through rain splash is increased, but the weed competition induces etiolation of the crop, resulting in internodes of greater length. Bennett and Cooke (2006) demonstrated that severity of *Septoria* sp. infection was not any greater in a conventional compared to a low-herbicide wheat crop, and an early study actually showed that the level of *Septoria* sp. infection is reduced by a clover under-story (Bannon and Cooke, 1998).
Resistance to *Septoria* spp. is one of the characteristics breeders focus on in their breeding programmes. Resistance to *Septoria nodorum* and *Septoria tritici* are listed in The Agronomist Handbook (NIAB 2007/08). Although these guidelines are useful for the latest growing season, there is considerable variation in the interaction between the isolate and variety in different regions (e.g. Ahmed *et al.*, 1995).

Septoria sp. over-winter in crop debris and the management of this material can assist in reducing early season inoculum supply although later in the season it is the weather conditions that influence the epidemic of *Septoria* sp. incidence (Shaw & Royle, 1989; Cook & Yarham, 1998).

As detailed above, the control of diseases in organic systems integrates crop rotation, with cropping diversity and a lack of excessive nutrition. However, these control measures are less valuable in the control of seed borne diseases such as bunt (*Tilletia tritici*) in wheat and loose smut (*Ustilago nuda* f. sp. *hordei*) in barley. This is because seed borne disease:

- fungi are generally not favoured by a high level of nutrition;
- are not soil borne, and therefore less influenced by rotations; and
- can rarely be controlled by the use of cereal mixtures due to legislative and supply chain limitations (Borgen, 2004)

Although the conventional sector breeders are not selecting for seed borne disease resistance because of the plethora of effective seed dressings (Wolfe *et al*., 2008), there is some variation in varietial resistance to seed borne diseases. In the Defra funded project OF0330, assessment of seed borne diseases indicated that the wheat varieties Hereward and Solstice both have a good level of resistance to bunt, and Exsept to *Microdochium*. Loose smut resistance was identified in Claire, Deben and Nijinsky, but all winter and spring barley varieties that were tested were susceptible.

Longer term studies in the 'ErgotLINK' project (REF) will determine whether the recent changes in the management of grass margins through CAP reform are implicated in the increased incidence of ergot (*Claviceps purpurea*) in cereals. The early work in the project has involved extensive monitoring of arable field margins, where a range of grass species have been identified with *C. purpurea*. It remains to be determined whether margin grass species are acting to bridge the gap between cereals in the rotation, and whether different varieties of wheat vary in their susceptibility to this disease (Bayles *et al.*, 2006)

For the organic sector, historical references identify a range of possible seed treatments that may be allowed in the organic sector. Heat and steam treatments have been shown to be effective, as well as bio-control agents and use of natural plant extracts (Borgen 2004). A recent evaluation of potential products and processes for the treatment of organic seed in the UK was carried out in the project OF0330. Effective management of bunt included the biological control treatment Cerall, and a novel biological product from Crompton Ltd. The hot air treatment and the Radiate (ammonium and zinc ammonium complex) were also successful. However, these are not yet commercially available.

The practice of farm saving seed raises concerns about the propagation of seed borne diseases. Diseases such as loose smut, bunt, and leaf stripe depend on multiplication through seed generations, whereas seedling blight is dependent on seasonal conditions, and the availability of external inoculum sources.

Across four seasons nearly 700 samples of seed from wheat, oats, barley and triticale were assessed for seed diseases in the project OF0330. The majority of samples were found to not exceed the threshold for disease on seed, with lower levels recorded in organic conditions. Importantly, the study did not identify any increasing disease problems from continually saving seed.

Management of disease in organic systems can be achieved by a combination of:

- Growing resistant varieties (as stated on National Listings);
- Having varieties that are awnless and taller;
- Avoid minimum tillage where the risk of FHB is high;
- Avoid growing two crops that are both susceptible to FHB in succession;
- Drill a clover under storey to control *Septoria* sp;
- Select varieties with resistance to seed borne diseases; and
- Test farm saved seed for disease levels.

Weed competitive ability

The weed competitive ability of a variety is defined by a range of characteristics, both above and below ground. The suitability of a variety for organic systems is also influenced by the developmental aspects of certain characteristics, such as leaf habit over time, and the interaction between the variety and its management.

A variety's light interception is defined by the interaction between growth habit, number of tillers, and height over time. A number of studies have highlighted single characteristics that improve weed competitiveness:

1. Early data from the OatLINK project (LK0954) showed that height, in naked and husked oat varieties (including new breeding lines), was the only characteristic that correlated with yield. This was suggested to be the result of the increased weed competitiveness above a certain threshold level; dwarf varieties, such as Hendon, are not suitable for organic systems (Jones *et al.*, 2006). Similar results were recorded by Murphy *et al.* (2008); in 63 old (over the last 100 years) and new wheat varieties height was the only factor that influenced weed mass.

2. More prostrate leaves intercept more light (Kruepl *et al.*, 2006; Hoad *et al.*, 2006).

3. A greater number of tillers increases ground cover (Kruepl *et al*., 2006; Hoad *et al.*, 2006).

4. Early establishment and height are characteristics that should be used to select for varieties for organic systems (Kruepl *et al*., 2006)

5. Increasing the seed rate can often accommodate more upright or 'erectophile' varieties, or those that have a lower tillering ability.

It has been demonstrated in wheat that weed competitive ability is a suitable characteristic for selecting in high yielding environments because 'competition' integrates a range of characteristics including early vigour, and good nutrient acquisition (Lemerle *et al.*, 2001). Hoad *et al.* (2006) suggest the wheat varieties Chablis, Rialto and Maris Widgeon have contrasting characteristics of a planophile habit, high tiller number and height, which would be useful in developing suitable organic varieties for Scotland. Winter wheat varieties that have performed well in terms of canopy cover, in the Defra project AR0914, are Deben and Soissons; this measure correlates better with yield performance than the data either for establishment or height (pers. Comm.).

The competitive ability of a variety below ground is influenced by the development of the roots and by the release of biochemicals that suppress the germination and development of other species (allelopathy). Bertholdsson and Jönsson (1994) screened 25 oat and barley varieties for their competitiveness against weeds. They found that greater than 50% of the variation in weed biomass was the result of differences in the rate of root development in barley, with no effect of shoot development. In contrast, the oat shoot and root growth rates influenced weed biomass equally.

Allelopathic activity (root exudates that inhibit the growth of other plant species) has been identified in oats, rye, wheat and barley (Kruepl *et al.*, 2006), but the level of activity varies both between and within species (Didon & Rodriguez, 2006; Bertholdsson, 2005). The assessment of allelopathy is difficult, a result of not only working with roots, but also the small concentration of phytotoxins and the temporal nature of toxin release. As a result, laboratory methods have been used to compare the level of allelopathy in the early stages of the various cereals, but little is known in the field (Bertholdsson, 2004). As a result, there have been no major activities to exploit allelopathic activity to date but it has been estimated that if the levels in wheat could be increased to that identified in barley, yields could increase by 58 – 66% (Bertholdsson, 2005).
In the absence of suitable weed competitive varieties, farmers commonly adopt the use of the hoe or the harrow for early season weeding. The tolerance of the different cereal varieties to mechanical weeding varies; in barley, varieties with lower weed competitiveness (shorter and with less dense canopy) generally had a greater tolerance to mechanical weeding (Rasmussen *et al.*, 2004), but no such trend was recorded in wheat (Murphy *et al.*, 2008).

Weed management can be improved in organic systems by selecting varieties with:

- Height;
- High tillering ability;
- Prostrate habit;
- Early establishment;
- Resistance to hoeing/harrowing;
- Allelopathic activity; and
- Extensive root development.

<u>Quality</u>

The quality of grain is defined by a range of characteristics such as the specific weight, Hagberg falling number, protein content and thousand grain weight. Further parameters are used as specifications in processing for different end uses such as alcohol yield in brewing and distilling, rheological properties in bread making and amino acid content for animal feed. Furthermore, the definition of ‘quality’ also relates to seed disease which has been discussed in an earlier section of this review.

The challenge to improve varieties for organic systems is two-pronged; in variety selection and the agronomy. The LK0960 project is evaluating different spring wheat varieties for milling, and the effect of different composts and manures on protein content. This work focuses on organic production systems, but most variety selection for organic systems relies on the NABIM grouping of varieties in the National Listings.

Analysis of some physiological parameters, such as N uptake, offers some potential for breeding milling wheat. For example, grain protein content is influenced more by the ability of a variety to remobilise nitrogen taken up before anthesis, rather than N taken up post-anthesis. By far the greatest proportion of N comes from that which has been stored in the form of proteins in leaves, stems and roots (Feller & Fischer, 1994). Therefore, varieties can be selected based on the nitrogen dynamics, as discussed earlier in this review.

In contrast to the relatively large discrepancies between organic and non-organically produced wheat, the oat varieties Mascani and Gerald had consistently good specific weights across management systems (LK0954).

Varieties grown for quality markets are based on decisions made from:

- National list specifications
- NUE
- Select for resistance to seed borne diseases

Selection

The basic premise for plant breeding is to select for the genotype (or plant genetic background) and therefore plant characteristics (the phenotype) that best suit the environmental conditions. A simple consideration of farm environments, not only for organic but also for high input systems, demonstrates variability in soil characteristics, climate, weed pressure, nutrient status and weed load and profile. Interactions between these characteristics further exacerbate differentiation between sites; for example, disease pressure is influenced by the weather, crop nutrient status and potentially by weed density. Further to these site considerations, the management practices are of course a major influence.
In principle, in order to achieve optimal varietal adaptation to one location all the breeding of that variety must take place at that site (Ceccarelli, 1996). In practice, plant breeding is restricted by the practical considerations of time and money. National programmes rely on developing genotypes for wide adaptation, and involve selecting genotypes in optimal conditions; in the absence of weeds, diseases and pests and with peak nutrient availability. This breeding approach has produced many successful pedigree line bred varieties for non-organic production systems. On the other hand, organic agriculture has suffered as a result of a lack of varieties that are better adapted to the environmental variability on organic farms (Wolfe *et al.*, 2008)

There are smaller breeding programmes in some countries such as Germany that have restricted the environmental range to the 'regional field condition'. The participatory breeding programmes that are now increasing in prominence are similar to plant breeding in the past, and focus on the 'local field conditions' (Desclaux *et al.*, 2007). The narrower the selection environment, with, for example, a smaller temperature range for the varieties to deal with, the better the adaptation of that variety to that restricted environment.

The difficulty arises in 'environment' classification, and even within farm management the variation is enormous (Wolfe *et al.*, 2008). The scope for selecting for suitable genotypes in farm location will be further discussed in the context of Suneson's (1956) 'evolutionary breeding'.

In organic conditions, the variability of the environment has a far greater influence on yield than the choice of variety (Wolfe *et al.*, 2008; AR0914). The level of adaptability of a single variety is not great enough to buffer the environmental variability across organic farms. This relative lack of stability has been demonstrated in a wide number of studies (e.g. Soliman & Allard, 1991; OF0330).

Physical mixtures of complementary varieties provide an improved ability of a crop to buffer variation in soil, climate and disease and weed pressures (Wolfe, 2001, LK0954, Didon & Rodriguez, 2006). Mixtures can also extend the life of a variety that has useful processing characteristics, but has sub-optimal performance criteria (Swanston *et al.*, 2006).

The diversity in cereal mixtures ensures a fraction of the varieties perform well in, for example, hotter drier conditions, whereas another fraction of the varieties yield better in wetter conditions. There is an enormous volume of literature citing the relative performance of mixtures to the component varieties, with some demonstrating a greater increase in yield for the mixtures (e.g. LK0954) and others better weed ccontrol. This variable success with mixtures is likely to relate firstly, to how much environmental variation a simple mixture of two or three varieties can buffer, and secondly the heterogeneity of the environment.

In low input and organic systems a large number of varieties mixed together can provide a greater buffering capacity, although the number of plant 'types' in a mixture is limited to how many varieties are incorporated (AR0914, LK0954). However, if varieties are artificially *crossed* together to create a 'population', a far greater range of possible characteristic-combinations can be created.

Populations (or composite cross populations) have been created for oats, barley and, more recently, wheat. In some cases the huge genetic diversity in the populations has successfully buffered environmental variability resulting in higher stability of performance (Suneson, 1956; Soliman & Allard, 1991; ARO914; Phillip & Powell, 1984).

If a farmer grows a population for one year, the plants that suit his farm will thrive compared to the weaker, less well-suited neighbours and will produce more seed. If that seed is re-sown over successive years, each year the better adapted plants produce more seed, such that over time the crop evolves to a particular farm (Suneson, 1956). Later generations of cereal populations produce higher yields than earlier ones, with an increase in height, protein content, disease resistance and a delayed maturity date (Suneson, 1956; Soliman & Allard, 1991, Mak & Harvey, 1982). This evolutionary breeding contrasts with pedigree line breeding and can lead to populations becoming site adapted.

The rate of evolution in composite cross populations depends upon the intensity and longevity of the selection pressure in a particular environment and the relative heritability of traits (David *et al.*, 1997; Danquah & Barrett, 2002; Choo *et al.*, 1980). Composite cross populations provide an exploitable method by which germplasm of older varieties can be conserved. In some cases, however, it has been shown that over successive generations of selection, this diversity is reduced, which results in a gradual reduction in stability (Soliman & Allard, 1991; Mak & Harvey, 1982).

The performance of a genotype (variety) or a combination of genotypes (mixtures and populations) depends upon the:

- Heterogeneity of a farm environment (high/low inputs);
- Breeding system (pedigree line, participatory breeding or evolutionary breeding);
- The diversity of the selection environment (number of sites and variation between sites); and
- The genetic diversity within the crop (variety/mixture/population).

<u>Commercial application</u>

The application of cereal varieties, mixtures and composite cross populations relative to varieties depends on the end use. Wolfe *et al.* (2008) relate the breeding approach to the use in three broad categories: '*Global commodity farming*' is purely driven by economics and uses predominantly modern varieties grown under high inputs producing a homogenous product for large industrial sized processing; '*Regional market farming*' has a low input focus, and involves both modern and older varieties - the product is more variable; and '*Local market farming*' is mainly carried out by farmers at a small scale, practical considerations include not only economics and low inputs, but also social and philosophical aspects (such as the conservation of genetic diversity). The capability of managing variability in the grain varies amongst these different supply chains. A local baker, for example, has the ability to adapt to seasonal product variation but in large processing operations strict regulations need to be adhered to regarding quality as well as the varieties used (B. Johnson, pers comm.).

Two major hurdles exist in the use of unusual varieties (e.g. not on the national lists), mixtures or populations: the perceived or actual heterogeneity of the product, and the legislation.

Grain used for milling and distilling is commonly blended at the mill/brewery to achieve the desired processing quality. So although there are major benefits in growing mixtures, particularly in low input conditions, the mixed grain cannot be sold for the milling/distilling premium. However there is some evidence to demonstrate the processing ability of mixtures. In a Dutch study, two and three-way mixtures of milling varieties performed better in terms of baking than the individual components of the mixture (Osman, 2006). For malting, there was no adverse effect of distilling four or five-way mixtures compared to their individual components (Swanston *et al.*, 2006). Finally, similar results were achieved with a pilot baking study of the 'quality' and 'yield-quality' composite cross populations of the Defra funded project AR0914 (Whitley, pers comm.).

The growing of mixtures avoids legal complications since the plant breeders' rights (PBR) can be applied to the individual components of the mixture, and the varieties of course abide by the DUS (Distinct, Uniform, Stable) and VCU (Value for Cultivation and Use) systems. The situation with composite cross populations is more complex.

No legislation exists for composite cross populations, such that there is no legal framework to trade grain on the open-market. The populations do not abide by the DUS or VCU system, but such heterogeneity, as discussed above has major advantages for production, particularly in less stable environments. For the farmer, the population material should be safe and reliable to grow, with a level of productivity and quality at least equivalent to current benchmark varieties grown under the same conditions. In terms of safety and reliability, a simple and effective approach would be one of traceability of the history of the population seed, indicating the provenance of the seed at each generation, which would include location, the farming system under which the crop had been grown and the purpose for which the population would be most suited. This would be in the form of a summary of the previous five years of production. It would also be essential to set a minimum size for a seed lot (say, 25kg), between generations, to ensure minimal risk of loss of genetic diversity from one generation to another. To further ensure the traceability, seed producers of populations should be required to join a Register of Population Seed Producers. Seed production and testing would follow the normal standards currently in place to allow for crop inspections, limits on weeds seeds, disease levels etc.

In the quality processing requirements discussed above, it has been assumed that organic products must align with the specifications for non-organic products. However, there is mounting evidence that the dissimilarities between organic and non-organic products are more extensive (Fauriel *et al.*, 2007; Hollmann *et al.*, 2007; Rembialkowska *et al.*, 2007; Sanders & Woodward, 2008). As a result, studies in LK0960 and in LK0999 focus on improving the processing of organic wheat by the actual modification of the production process. No evidence was found of research with a focus of changing the processing standards in other cereals.

The commercial application of varieties, mixtures and populations relates to:

- the supply network (global/regional/local);
- close cooperation with processors; and
- the legislative framework.

3. Analysis and Conclusions

Varieties & selection

The nature of competition is complex; varieties that are equally competitive can have different combinations of characteristics. As a result, selection of suitable genotypes should be based on measurable components of performance that are indicative for a range of physiological functions. This review has described a number of growth characteristics that influence more than a single physiological function, for example early tillering which improves weed competitive ability, and may also improve the nitrogen dynamics of that variety in organic systems. Therefore, selection criteria in breeding should favour characteristics that integrate valuable physiological functions.

In the absence of agrochemical inputs, the interaction between crop physiology, the environment and management is complex. Therefore, the selection of genotypes for organic systems should take place under organic conditions. Low input breeding programmes have produced a number of relatively successful varieties such as Pegassos (FR Strube). However, early indications suggest that yield variability between years can still be significant (WheatLINK LK0970).

An alternative approach, to deal with a greater level of environmental heterogeneity is to grow mixtures or populations. The diversity within mixtures, and therefore the buffering capacity, is limited to the number of component varieties. Furthermore, these varieties have not been selected for local environmental conditions. If better environmental adaptation results in higher yields, the way around the issue of site selection can be dealt with by using evolutionary plant breeding. Populations produce a greater range of plant characteristics as a result of inter-crossing varieties. The diversity of the population has been shown to significantly buffer environmental variability, maintaining stable, higher than average yields.

Cereal populations are pertinent to the agricultural challenges of the future. The drive for top yielding varieties under optimum conditions will be superseded by reducing oil based inputs, and maintaining disease resistance in an increasingly unstable environment.

Management & systems

The production of cereals is just a single component of the organic rotation. This review has briefly mentioned Fusarium head blight as an example of how the whole farm system needs to be considered for the management of this disease.

The choice of cereal species and variety (such as a variety's performance with an under-sown crop), and the value of straw is further influenced by soil fertility and associated livestock enterprises. Therefore, a rotational approach is essential in deciding which species, varieties, mixtures and/or populations to grow.
Finally, in support of cereal populations, the site adaptation of these crops can have major advantages, for example having a crop that has adapted to under-sowing, mechanical weeding and early sowing.

Further work

In the short term, pedigree line variety selection under organic conditions for organic systems could provide advantages including improved weed competition, and nitrogen use efficiency. This organic selection is being carried out in Germany with relative success. Farmers in the UK may benefit from outputs from these breeding programmes in the near future.

Extensive consultation needs to take place in the development of mixtures and most importantly of cereal populations. This breeding material potentially offers real solutions to the challenges organic farmers are facing now, and the predicted problems of the future. Farmers, breeders, millers, bakers, maltsters and all other members of the cereal food chain need to address the problems with supply, management of the genetic diversity, and production consistency and legislation. Only then will the problems that need to be addressed be differentiated from the perceived issues that limit the development of arable production.

4. Summary and Discussion for advisers

Summary

This research review notes that cereal variety breeding in the last 50 years has been based on pedigree line bred varieties as part of the development of a production system dependent on oil-based inputs. The characteristics desirable for an organic system are frequently at odds with those designed for non-organic systems. Despite this, varietal choice for organic farmers remains largely from the pool of varieties developed for non-organic production. The challenges to address are on what basis can farmers and advisers select varieties, and how to develop varieties suitable for organic production.

Plant characteristics are discussed and main desirable features outlined under the headings of:

- Nutrient use efficiency
- Disease resistance
- Weed competitive ability
- Quality

Breeding selection parameters are then considered. The wide variation that occurs in organic systems and the aim to improve the consistency of performance (yield stability) means that the adaptability of a single variety is not sufficient to buffer these variables. The place for variety mixes is considered, and then the case for composite cross populations. The development of these alternative approaches is hindered by market acceptability and for composite populations by the legislative framework.

The conclusions note there are many and different combinations of characteristics that may be of advantage. The suitability of a variety can be affected by the management of the whole organic system, not just one crop in isolation. The situation is complex and selection of genotypes is best undertaken under organic management. Low input line breeding programmes have achieved some success, but the review argues that better environmental adaptation is achieved by genotype diversity, either as variety mixes or as composite populations.

For the future there is potential in the (relatively) short term for line breeding under organic conditions. For the longer term there is opportunity in mixtures, and especially of populations. For these to be successfully developed there is a need to address cultural attitudes, inertia in the market and production infrastructure and legislative framework.

Discussion

The review draws together many reports and suggested characteristics desirable for organic production. In addition there are notes on some of the cultural interactions to consider. These give guidelines that should inform breeding programmes and be helpful for an adviser/farmer to select varieties, and goes on to effectively recommend the development and adoption of mixed genotype cropping. This discussion focuses on advisory aspects raised by this review.

1.0 Current variety selection

In practice the majority of organically grown cereal crops in the UK are of a single variety stand, how do organic farmers choose which variety to grow? There is very limited variety testing under organic conditions. A truly comprehensive programme that covered the noted wide variation in organic systems and could prove yield stability over time is never likely to be funded.

Currently choices are generally made on the basis of:

- past experience
- the availability of varieties as organic
- limited trials information
- observations and recommendations from other farmers, advisers and seed suppliers

The selection of which new varieties to bring into organic seed production is largely based on choices made by seed companies, hopefully informed by many of the types of characteristics outlined in this review. Some farmers will be making these observations and choices for themselves.

Can these desirable traits be used as a checklist for variety selection? The availability of information as to all of these traits is limited, the HGCA recommended and descriptive lists cover some of the aspects from variety trials conducted under non-organic management. Information on other traits in a usefully comparative way is not readily available.

2.0 Using traits outlined in the review

2.1 Nutrient use efficiency

- early season N uptake followed by internal translocation of N at grain filling;

  is there information on different variety characteristics? Is this related to rate of apical development? HGCA winter wheat recommended lists do give a ‘speed of development to GS31’ for 3 different sowing dates; is this a useful indicator?

- higher nutrient use efficiency (NUE);
  the review notes significant differences in barley varieties has been demonstrated, but is this information available for all varieties, if so, where is it published? Can information on all cereals be made available?

- a higher number of tillers;
  tiller numbers are not recorded in recommended lists. Tillering can be affected by plant spatial arrangement and density, drilling date and background nutrition. Some data on tillering capacity should be able to be available.

- longer, and a greater number of root hairs;
  particularly useful in low phosphate situations, is this information that plant breeders routinely have available?

- beneficial microbial associations;
  can more information on varietal differences be gathered and be made available

- delayed senescence;
  associated with higher protein content. The recommended lists give days to ripening compared to a standard for all species (for current NABIM Group 1 varieties, this is a maximum of + or – 1day).

2.2 Disease resistance

- Growing resistant varieties (as stated on National Listings);
  disease resistance to the main foliar diseases is noted in HGCA recommended lists, but not on the descriptive lists for triticale and rye

- Having varieties that are awnless and taller;
  applies to wheat and ear disease, recommended lists give a height figure, but do not indicate whether awned or not.

- Select varieties with resistance to seed borne diseases;
  evidence of varietal variation in wheat, but information not routinely available

2.3 Weed competitive ability

- Height;
  height or straw length is noted in recommended and descriptive lists

- High tillering ability;
  as above

- Prostrate habit;
  prostrate/erect, planophile/erectophile leaf habit and leaf size are noted in variety description but not in recommended or descriptive lists. Growth habit can be influenced by plant spatial arrangement and growth stage.

- Early establishment;
  information not readily available, but wheat recommended lists do indicate speed of development to GS31 for 3 different sowing dates

- Tolerance to hoeing/harrowing;

Some limited evidence of differences in barley, is this a reflection of growth habit?

- Extensive root development
  information on varietal differences not readily available

- Allelopathic activity;
  an area that appears to offer great potential but about which so little is understood in field conditions. More research is needed before allelopathy becomes a manageable consideration in variety choice.

2.4 Quality

Recommended and descriptive lists note the quality characteristics of varieties. The reliability with which organic wheat varieties achieve milling grade protein levels appears to be greatly affected by site. Indications from samples submitted to grain merchants and from some comparative studies suggest that spring wheat varieties are more reliable than winter varieties.

2.5 Summary

Choice of variety is only one of the management decisions to be made and variety traits are not, in isolation, reason to reject a variety. For instance, Claire is rated in the recommended list as poor for mildew resistance and is not particularly tall, likewise Hereward is not particularly tall, has a relatively erect growth habit and does not tiller strongly, but both of these varieties have performed with good consistency under organic management. Such varietal traits can be used to inform other management decisions, for instance Hereward's limitations should affect seed rates, spatial arrangement and avoid weedy sites.

To aid variety selection there is a case for drawing together information on variety traits outlined above. Some information is readily available, some is produced but not published and some is not currently investigated. However, these are only guides and there remains a need for some form of variety assessment in organic management based on field performance. This could involve use of actual field performance so long as it is reliably reported by farmers, complemented by limited field trials/studies. It is notable that a successful variety in the organic sector tends to have a long life compared to the rapid turnover of varieties in the non-organic sector.

3.0 Selection

The review shows the value of mixed genotypes to cope with diverse environmental factors. The concept has been proven in studies but variety mixes have still not gained wide acceptance and populations are even further from the option of widespread commercial use.

The benefits of variety mixes have been made apparent for many years, the current market infrastructure and farming culture has yet to be adapted. There is a case for an ongoing co-ordinated advisory project aiming to promote the uptake of this practice aiming to encourage producers, end users and seed suppliers. This in turn could be a step towards acceptability of mixed populations and development of an appropriate legal framework and change in market acceptability.

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