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Integration of breeding and technology into diversification strategies for disease control in modern agriculture

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Abstract While diversity for resistance has been recognised for more than 60 years as a key factor in disease management, and diversification strategies such as cultivar mixtures and multilines are described and advocated in almost every plant pathology textbook, the general view in modern agriculture is that diversity would be too difficult and expensive to implement. In addition, difficulties in marketing the produce are emphasised. The question thus arises if and how such strategies can be designed to find a place in modern agriculture. Considering the general ecological benefits of diversification and the possible economical benefits for growers and society, several possible approaches to the solution of actual and perceived problems in modern agriculture are discussed. An important route towards achieving diversity would be to integrate it into the breeding process. Selection criteria would include inducibility of resistance and competitive ability, in order to produce diversified varieties able to adapt both to unpredictable environmental conditions (especially climatic) and to changing pest and pathogen populations through co-evolution. Evolutionary breeding methods such as composite crosses and modern landraces and some of the legal problems associated with these approaches are discussed. Technical solutions are integral to the future use of diversification strategies and range from more or less simple adjustments to machinery for planting and harvesting to devices designed for separation of the harvested products.

Keywords Mixtures · Intercropping · Composite crosses · Evolutionary breeding · Co-evolution · Plant varietal protection

Introduction

Since the advent of modern plant breeding in the early twentieth century, the trends in agriculture have been towards genetic uniformity within crops. This has greatly enhanced possibilities for mechanisation in agriculture. However, this has resulted simultaneously in major losses in agricultural biodiversity (Fowler and Mooney 1990). Much of the resilience of agricultural ecosystems is due to complex interactions among species and genotypes at all levels of the system (inter- and intra-specific) and there are many examples throughout the nineteenth and twentieth century which demonstrate how a lack of diversity for resistance within crops renders crops and whole agricultural systems vulnerable to pest and disease attacks (e.g. Harlan 1972; Ullstrup 1972; Trenbath 1977; Juska et al. 1997). By the middle of the twentieth century breeders and pathologists realised that while "plant

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diseases are shifting enemies" (Stakman 1947), reacting to changes in host resistance with continuous adaptation human interference with crop genetic make-up may pose dangers. These are best described with the following quote: "...by the wide use of hybrid corn we are depriving this important crop of its power of taking care of itself and by continued crossing and variation continually adjusting itself to the equally variable parasites which attack it" (Stevens 1942).

In reaction to the recognition of the dangers of genetic uniformity, diversification concepts have been developed by pathologists and breeders since the 1950s (see Wolfe and Finckh 1997 for review). Diversification strategies in time and space are being used in many agricultural systems to achieve acceptable levels of important diseases, pests, and weeds together with high product quality and stable yields (Finckh and Wolfe 2006).

There are a great number of possibilities for diversifying cropping systems, ranging from diversification of resistance genes within monoculture systems (multilines, cultivar mixtures) to species mixtures and very complex perennial polyculture (Finckh and Wolfe 2006). Polyculture systems in particular are usually designed to achieve many ecological benefits such as control of erosion, weeds, pests and diseases together with improved soil fertility (Altieri 1995; Altieri et al. 1996). While the focus of this paper is on crop diseases, implications for pests, weeds and other problems will also be considered to show how system modifications can be introduced which ultimately reduce costs, increase production and reduce stress on the environment.

The purpose of this paper is to give an overview of the effects of diversity on diseases and the wider ecological benefits of diversity. While much of the benefits of diversity are seen in intercropped systems, the focus here is largely on intraspecific diversity or intercropping in modern agriculture. Subsequently, the integration of breeding for diversity-including some of the legal implications-and technological approaches needed to achieve greater diversity within the agricultural system are discussed.

Effects of diversity on diseases

While monoculture usually refers to the continuous use of a single crop species over a large area, it is important to clearly differentiate the different types of monoculture that exist in agriculture with respect to pests and pathogens (Finckh and Wolfe 2006). Monocultures also exist at the level of species, variety or gene. For example, within a species monoculture, farmers can diversify among different varieties which exhibit different disease resistance genotypes. However, many of the modern varieties of a given species often possess the same gene(s) for resistance to a particular pathogen, resulting in a monoculture with respect to that resistance (resistance gene monoculture). A current example in western and central Europe is the use of the *mlo*-resistance to barley powdery mildew (caused by *Blumeria graminis*) in about 60% of the area presently grown with spring barley (Schwarzbach, personal communication). Monoculture of susceptibility has led to many catastrophic losses in, for example, potatoes, coffee, grapes, elms, or chestnuts during the nineteenth and twentieth century. The losses usually occurred in the wake of accidental intercontinental pest- and pathogen migrations. However, even without such migration events, many plant disease epidemics occur as a consequence of the cultivation of genetically uniform crops over large areas and thus, plant disease epidemics may be 'normal agricultural accidents' (Juska et al. 1997) due to the breeding for uniformity and the use of too few differentially resistant varieties in space and time.

Diversity that limits pathogen and pest expansion and that is designed to make use of knowledge about host-pest/pathogen interactions to direct pathogen evolution has been termed functional diversity (Schmidt 1978). The mechanisms leading to disease reduction in diversified systems will only be summarised here as there are several detailed recent reviews of the subject (Finckh and Wolfe 2006, Finckh et al. 2000; Mundt 2002).

On a mechanistic level, an increased distance between plants with the same susceptibility and the barrier function of differentially susceptible plants in between play a major role. In addition, microclimatic effects due to differences in crop architecture may become important, especially when plants are grown in alternating rows or strips. For example, in south western China, single rows of highly susceptible tall rice cultivars are interspersed in between several rows of dwarf hybrids (Fig. 1). In addition to the distance effects, reduced lodging of the tall plants and reduced

Fig. 1 Rice cultivar mixtures in China. Single rows of tall traditional varieties are interspersed within fields of high yielding hybrid cultivars (source: own photograph)

relative humidity in the well-aerated tall rice lead to reductions in rice neck blast severity (caused by *Pyricularia grisea*) from 40% to 50% to 4% to 5% (Zhu et al. 2005). But even in more intricate cultivar mixtures of wheat, e.g., differing in height, microclimatic conditions in the crop canopy may be drier than in uniform stands.

Overall, in species mixtures, the nutrient use efficiency is usually increased due to niche differentiation of the different crops (Tilman et al. 2001). While I am not aware of direct measurements of such effects in intraspecific mixtures, this may be true for these too, provided there are differences in nutrient uptake patterns and root spatial distribution. Differences in the microbial communities associated with the rhizosphere influencing plant health (termed plant probiotic microorganisms, PPM) are variety-specific (Picard and Bosco 2007) and it is likely that PPMs may also affect the nutrient availability and uptake (Picard et al. 2008). In addition, increased or decreased competition among plants due to differential infections may lead to the favouring of more resistant genotypes and allow for compensation of yield losses (Finckh and Mundt 1996; Finckh et al. 2000). Therefore, yield stability (i.e. consistent high yield over a range of environments) is commonly greater in mixtures than in pure stands. In large data sets, the treatment variance (mean square error) has been shown to be a good measure of yield stability (e.g. Allard 1961; Finckh et al. 2000).

On the pathogen side, different pathogens and pathotypes of a given pathogen may interfere by competing with each other for available host space (e.g. Lannou et al. 2005), resistance induction (e.g. Chin et al. 1984; Calonnec et al. 1996; Lannou et al. 2005), and possibly other unknown mechanisms. As host diversity favours diversity among pathogens, it will increase the chances of avirulent pathotypes occurring on a given host genotype. This, in return will enhance induced resistance in the system. This was shown impressively for yellow rust of wheat (Calonnec et al. 1996; Finckh et al. 2000).

Scale effects of diversification strategies are important but often not considered: as the area planted to a given host genotype increases, so does the amount of inoculum produced by this genotype and consequently the contribution of regional dispersal to epidemic development. Conversely, as the area sown to mixtures increases and the overall disease severity decreases, regional dispersal will also be reduced. While it is almost impossible to demonstrate this experimentally, results from a computer modelling study by Mundt and Brophy (1988) demonstrated this effect (Table 1). Also, when used on more than 300,000 ha in the former German Democratic Republic, powdery mildew of barley was reduced by 80% in barley cultivar mixtures within five years (Wolfe 1992).

If cultivar mixtures or multilines are used over time, there will also be evolutionary responses of the

Table 1 Effect of scale of diversification on area under the disease progress curve (AUDC) in computer simulated epidemics

Number of fields	Total Area (ha)	AUDC	
		Non-diversified	Diversified
4	10	92	70 (0.75)
16	38	127	75 (0.59)
64	154	172	83 (0.48)
256	614	218	91 (0.41)
1,024	2,458	261	89 (0.38)

In the study, either all fields were susceptible (non-diversified) or 75% of the fields resistant (diversified). Numbers in parentheses represent the relative disease in the diversified compared to the non-diversified situation (data from Mundt and Brophy 1988)

pathogens which could lead to the development of so-called super-races, i.e. pathotypes able to attack all genotypes in the mixtures, if the same type of host diversity is used continuously (see Mundt 2002; Wolfe and Finckh 1997; Finckh et al. 2000 for reviews). Thus, care has to be taken to either change the host resistances used over time or to allow for evolutionary responses on the host side (see below).

The described mechanisms have been shown to work well in reducing incidence and severity not only for more or less specialised wind and also some rain splash-dispersed foliar pathogens of cereals but also for other crops such as coffee (see Finckh and Wolfe 2006 for review). For potato late blight (caused by *Phytophthora infestans*), however, only moderate to insignificant effects of cultivar mixtures or plantings in alternating rows and strips of differentially susceptible varieties have been reported (Andrivon et al. 2003; Garrett and Mundt 2000; Phillips et al. 2005; Stolz et al. 2003) with greater mixture effects under moderate natural inoculum pressure than under high natural inoculum pressure (Garrett et al. 2001; Pilet et al. 2006). Part of the explanation for these results may be that, at least in Europe, most race-specific resistances have been overcome and we have observed that in mixtures and alternating row plantings of potato varieties differing in partial resistance, the more susceptible varieties were less diseased than in pure stands but the more resistant varieties were more diseased (Stolz et al. 2003 and own unpublished data). However, intercropping potatoes with strips of non-hosts led to significant disease reductions in field experiments over three years (Finckh et al. 2005; Bouws and Finckh 2008). The reductions were due to reduced initial inoculum in smaller plots, reduced infection rates, changes in microclimatic conditions and, most importantly, loss of inoculum from strips planted perpendicular to the prevailing wind direction (Bouws and Finckh 2008). Late blight epidemics are usually started either through seed-borne infections or by wind-borne inoculum. In smaller fields, the absolute number of seed-borne infections per field as well as the probability of inoculation by an inoculum cloud is lower than in large fields. This should lead, on average, to a later epidemic start in smaller fields. Experimentally, this can only be tested without artificial inoculation. In the intercropping experiments of Bouws and Finckh (2008) the variable start of the epidemics was clearly visible and a detailed geostatistical analysis of the data showed the effects of plot size and plot location in the field (upwind/ downwind, neighbour spring wheat or grass-clover; Finckh et al., unpublished data).

Comparison of different management methods such as strips and whole fields in a meaningful way, has to be done on-farm and in different fields. Late blight epidemics in pure stands of potatoes grown in strips 12 m wide and 50 m long planted perpendicular to the prevailing wind direction, were compared with epidemics in regular potato fields on four commercial organic farms. Copper applications were tested as an additional factor. Overall, disease severity was highly variable among the different sites and field locations within sites with no obvious effect of cropping pattern. However, when copper was applied, the area under the disease progress curve in whole fields was reduced by an average of 23% but by 34% in the strips. It is likely that this was due to a greater loss of inoculum out of the strips than of the field (Finckh et al., unpublished data). In a theoretical modelling approach, Skelsey et al. (2005) predicted about 40% reductions in what the authors called ‘final disease severity’ on single potato rows surrounded by resistant plants in fields surrounded by non-hosts. However, as the simulations were stopped long before any spores could reach field edges, final disease severity in the model was not even 50% in the pure stands. In contrast, the complete epidemics were compared in our field experiments. It would be highly interesting to include wind direction, variable amounts of randomly distributed inoculum, and genotype units consisting of several rows into this model.

While late blight was reduced in strip-cropped potatoes, we also found that the outer rows of the potatoes in the strips often suffered from competition by neighbouring cereals (but not grass-clover) making it necessary to find a balance between epidemiological benefits and possible negative effects on the yield of the edge rows. This example shows that, despite positive effects of diversification strategies on diseases, these effects may not always translate into yield benefits. Care has to be taken that crops and species are truly amenable to mixing. While in variety mixtures, potatoes may still yield better overall than in pure stands (Phillips et al. 2005), in cassava (*Manihot esculenta*), significantly reduced yields were observed in cultivar and species mixtures as compared with pure stands, leading to the recommendation to plant small fields of pure stands separated by different crops for erosion control, e.g. rather than using intricate mixtures (Daellenbach et al. 2005).

Where intercropping is not an option, because of competition or the lack of appropriate partners for a system, mulches may offer solutions. For example, virus infestation levels of organic potatoes were significantly reduced by applying straw mulch in between the rows which reduced host finding by aphids (Saucke and Döring 2004). In addition, erosion was reduced by > 90% and after harvest, soil mineral nitrogen was prevented from leaching (Döring et al. 2005).

Diversification in time through crop rotation may deprive pathogens of their hosts for one to several seasons, thereby reducing inoculum of specialised pathogens substantially. In addition, certain green manure and other crops may have direct negative effects on pathogens and weeds due to allelopathy. For example, certain *Brassica* species release volatile compounds that have direct inhibitory effects on the growth of many pathogens (e.g. Gimsing and Kirkegaard 2006; Kasuya et al. 2006; Mayton et al. 1996). Other crops such as hairy vetch (*Vicia villosa*; Zhou and Everts 2004) as well as various oat species and varieties, have been found to suppress several soil-borne pathogens including nematodes (Elmer and LaMondia 1999; Vilich 1993).

Besides pathogen starvation, different soil tillage practices applied to different crops in the rotation help reduce weed seed banks, and usually, soil microbial activity and soil fertility are increased by crop rotation. Thus, yields of winter wheat could only be maximised when grown after a pre-crop other than wheat even when fungicides were applied (Odoerfer et al. 1994; Table 2).

Integrating breeding and technological approaches to achieve diversity within the agricultural system

Despite the described positive effects of diversity, modern agriculture is based on monocultures, which are therefore targeted by current breeding programmes. Consequently, the ideotype of modern wheat has been defined as being relatively non-competitive to allow for dense pure stands (Hamblin and Donald 1974). It is for this reason, that most of the currently available crop varieties are not necessarily amenable to mixed cropping and there is a need to develop genetic resources adapted to diversified growing systems. In addition, managerial, legal, and technological problems have to be tackled.

Genetic resources for mixed cropping

Diversity can be achieved at the level of species, varieties or genes within species, variety mixtures as well as multilines in use worldwide (Finckh and Wolfe 2006). In contemporary usage of cultivar mixtures, the components have not been selected for performance in mixtures. It is unlikely, therefore, that

Table 2 Effects of different pre-crops and fungicide sprays on leaf diseases of wheat caused by *Drechslera tritici-repentis* (DTR) and *Septoria tritici* and on yields of wheat

Pre-crop	% Diseased leaf area with DTR and *S. tritici*		Yield (t ha^{-1})	
	No fungicide	Fungicide	No fungicide	Fungicide
Winter wheat	43	4	6.77	7.67
Faba beans	5	0	8.76	10.02
Red clover	7	1	8.39	9.38
Winter rape	5	0	7.98	8.69
Maize	13	0	7.43	8.26

Data from Odoerfer et al. 1994

they will perform as well as lines selected for mixture use, although even in pedigree line breeding programmes, the F1 and F2 generations are usually grown as populations. However, for example, beans that had evolved within a composite cross were more amenable to mixed cropping than beans selected early in the breeding process as pure lines (Allard 1961). Some trial results suggest that tests of two-way mixtures can provide useful indications of specific and general mixing ability for predicting performance of more complex mixtures of wheat (Knott and Mundt 1990; Lopez and Mundt 2000; Mille et al. 2006), barley (Gacek et al. 1996) and even potatoes (Phillips et al. 2005) in terms of both yield and disease restriction.

While the mixture strategies contribute substantially to plant protection, they all are based on at least a periodical remixing of the host populations. In this way, while the pathogen populations adapt constantly through natural selection, there is no possibility for reciprocal evolution on the host side, i.e. co-evolution does not happen. Before the advent of modern plant breeding, locally evolved and usually genetically diverse crop landraces were grown, and where landraces are still in use, these are often diverse for resistances to pests and pathogens. Thus, rice landraces in Bhutan differed in their resistance to rice blast (caused by *Pyricularia grisea*) among environments due to varying selective pressures (Thinlay 1998; Thinlay et al. 2000). Similarly, high diversity for resistance has been found in barley landraces in the Middle East (van Leur et al. 1989) and in phaseolus beans in Rwanda (Trutmann et al. 1993). Where landraces are still being used by growers, different approaches have been used to maintain their diversity and adaptability and some research is geared towards showing the role of diverse landraces in plant protection (see Jarvis et al. 2007 for review). Approaches being made use of in attempts to increase population resistance and yield potential while maintaining diversity include farmer participatory breeding (Ceccarelli et al. 2000), top-crosses (Yadav et al. 2000), partial replacement of local varieties through high yielding and/ or resistant varieties (Trutmann and Pyndji 1994) or population selection out of landraces (Finckh 2003).

Because of the absence of landraces in modern agriculture and also their low attractiveness in terms of yield and quality in comparison to modern varieties, Murphy et al. (2004) called for new approaches to the development and selection of what they termed ‘modern landraces’. These are bulk populations developed from superior germplasm and further subjected to local selection, or even farmer participatory improvement, using simple selection schemes that enable farmers to “breed crop varieties and landraces that will help improve the sustainability and profitability of their farm” (Murphy et al. 2004). Such an approach to the development of high yielding, but also highly diverse and adaptable plant populations, was already taken in California during the first half of the twentieth century (Harlan and Martini 1929) and later termed ‘evolutionary plant breeding’ (Suneson 1956). Through composite crosses (CC), i.e. the crossing in all possible combinations of several to many parental lines (Jain and Qualset 1975), genetically diverse populations were created that were later subjected to mass selection under different environmental conditions, a process mimicking the development of landraces while integrating the advantages of modern high yielding and high quality varieties.

Composite crosses have been made for barley, oats, wheat, phaseolus beans (see Phillips and Wolfe 2005 for review), and faba beans (Ghaouti et al. 2005). For barley, the CC approach has been shown to be extremely powerful: innumerable elite varieties released in the twentieth century trace their origin to the CC populations produced in California in the 1920s while the CC populations have remained genetically variable even after 50 generations of propagation at single sites (Allard 1988). When exposed to new environments including diseases that had not been important in the original environment, the CC populations proved to be readily adaptable to these (e.g., Danquah and Barrett 2002a, b; Hensleigh et al. 1992; Webster et al. 1986). Similarly, French work on dynamic management of wheat CCs shows that adaptive changes within the populations in response to local selection pressures occur, while simultaneously maintaining genetic variation and thus adaptability (Goldringer et al. 2006).

Several varieties that were not based on pure lines were selected from the barley CCs with varying success (Suneson 1956; Jain and Qualset 1975). More recently, wheat breeders at Washington State University (Dawson et al. 2006) and in Europe (Wolfe et al. 2006) have taken a similar approach for low-input wheat. Thus, such approaches to diversification in the breeding process may be taken in areas where landraces do not play an important role any more. This would contribute to an overall diversification of the agricultural system and, at the same time to dynamic development and conservation of genetic resources. The advantage of the modern landrace approach is that selection for the ability to be grown in diversified systems is favoured. In addition, increased intra-varietal diversity may become more and more important in a future of rapidly changing and unpredictable climatic conditions.

While intra-varietal diversity might be important in the longer-term evolutionary context, it will only be of interest for practical use if yield levels and stability are comparable to pure lines or variety mixtures. For wheat, early work has shown increased yields in the F2 over physical mixtures (Qualset 1968). In an initial comparison of three wheat composite crosses with mixtures of their parental lines in four different sites, the composite crosses had higher yields in 11 out of 12 cases in 2005 (Wolfe et al. 2006). In 2006, results were similar but not in 2007 (Wolfe and Jones, personal communication). Polycross progenies of winter and spring faba beans tested in four sites over three years yielded significantly higher than the inbred parental lines, while the variances of the polycrosses were significantly lower, indicating superior yielding ability and stability (Ghaouti et al. 2005; Ghaouti and Link 2007).

Little formal research has been conducted into breeding for multiple cropping and mixtures (for review see Francis 1990). However, farmers often have long-standing experience in growing mixtures and may be an important resource for breeders. Thus, the success of heterogeneous bean varieties in Rwanda was greater when selected by local farmers than when selected by breeders (Sperling et al. 1993). Since 2004, a European COST project on ‘Sustainable low-input cereal production: required varietal characteristics and crop diversity’ (see www.COST860.DK) is addressing issues of breeding and diversification, bringing together scientists from more than 20 countries. There is also growing interest in organic, sustainable, and participatory breeding approaches as documented by several recent conferences (see website above) including the creation of a new section on sustainable and organic breeding within EUCARPIA (European Association for Plant Breeding Research) on November 7, 2007.

Legal considerations

If variety and species mixtures are to be sold as seed, the exact amount of each mixture component has to be stated by law. This precludes the production of mixtures from mixtures for sale, as the component frequencies in such seed mixtures will differ from the original frequencies. Producing pure lines and mixing these is, however, less efficient than simply producing mixed seed, making mixture seed often more expensive.

Registration of diversified varieties presents legal difficulties both in Europe and in the USA because of the Union for the Protection of New Varieties (UPOV) guidelines or EU rules (Regulation 2100/94/EC) and the Plant Varietal Protection Act (PVPA) in the USA, which require that a variety must be uniform genetically and in appearance and be readily distinguishable from other varieties in order to be accepted for registration. Over the past 50 years, innumerable varieties and landraces have disappeared from the market because they did not fulfill the legal requirements. For example, it has been estimated that approximately 75% of all vegetable varieties in Europe have disappeared within 10 years since the inception of UPOV in 1961 (Mooney 1979). Indeed, great concern has been voiced world-wide about the precipitous genetic erosion in agriculture due to legislative measures, general breeding methods and genetic engineering technology (e.g. Fowler and Mooney 1990; Kloppenburg 2004). Besides some local national provisions for the maintenance and limited circulation of landraces (i.e. already existing diverse populations), there is no provision for the release of newly bred diversified varieties such as composite crosses, or top crosses, since they do not comply with current law.

Technological and managerial questions

There may be technological limits to the mixture concept where mixtures are not desirable or special quality requirements have to be met. However, many products are the result of mixing. Thus, maltsters usually mix different varieties together for malting to achieve a desired malting quality and the malting quality of a batch of barley is dependent much more on the conditions under which it was grown than on the individual variety. Furthermore, variety mixtures of the same quality class can provide a more stable quality across environments than the single component varieties (Baumer 1983). Similarly, in the former German Democratic Republic, breeders and brewers cooperated closely to achieve high quality malting barley cultivar mixtures (Wolfe 1992). For wheat, millers mix together different batches of grain to obtain the quality requirements of processors. This can also be achieved with cultivar mixtures and where farmers and bakers directly cooperate, e.g. it is common practice in the organic sector (personal observation). While in general, it is difficult to market mixtures in Europe, no such difficulty exists in the USA, as documented by the large area grown with wheat cultivar mixtures (Finckh and Wolfe 2006).

While coffee is a particularly sensitive crop from the point of view of quality some of the best coffee worldwide is produced in Colombia from more than 350,000 ha of mixtures that have been selected to be variable in terms of rust resistance but uniform for quality characteristics (Moreno-Ruiz and Castillo-Zapata 1990).

The Chinese example with rice in strips (Fig. 1, Zhu et al. 2005) is successful because the tall traditional varieties fetch a premium price on the market and they are harvested manually before the hybrids. Where the agricultural system is fully mechanised, however, strips of the width of commonly used machines should be chosen.

Introducing different crops into highly specialised farming operations usually requires additional know-how and machinery. Many of the beneficial break crops such as grass-clover are only useful if animals are present on the farm to make use of them. While green manure crops are an option on stockless farms, care has to be taken to prevent leaching of nutrients. Either cooperation between animal producers and stockless farmers or the integration of biomass production for biofuels may offer solutions.

Farmers often argue that the extra labour required when changing field sizes and arrangements will not pay. Net returns were estimated for the four on-farm potato strip intercropping experiments described above in comparison to normal fields. It was estimated that up to six more person hours ha^{-1} and season will be required for the management of strips including all operations (four copper applications) from planting to harvest. In three of the four farms, slightly higher net returns were realised from strip-cropped potatoes, twice in unsprayed strips and once in sprayed strips (own unpublished results).

Farmers and agricultural engineers continuously develop and adapt machinery for new applications. Row or strip intercropping is often practiced with the help of adapted machinery, especially in vegetable cultures, where machines are usually smaller, and strip or row-application of fertilisers, compost or agro-chemicals is already common practice. Machinery for direct drilling and for undersowing does exist and mechanical separation of seed mixtures where different seed sizes are involved (e.g. faba bean-cereal mixtures) is practiced by some farmers (personal observation). Modern optics might offer solutions for post-harvest separation of fruits or vegetables.

Conclusions

Adaptability and buffering capacity are the product of functional diversity and the ability of crops to evolve. Considering current environmental problems such as erosion and global warming and the reduced predictability of the local climate, there are a number of breeding goals that need to be taken care of at the same time. Besides yield and quality, the ability to adjust to changing environments is especially important. Any properties that increase erosion control and/or allow for reduced inputs such as competitiveness against weeds, better soil cover, pest and disease resistance, as well as nutrient use efficiency will increase in importance.

While the positive effects of functional diversity for resistance but also for other important traits providing ecosystems services such as erosion control, reduced nutrient leaching and genetic resource conservation, are well known, there are many apparent and true technological and legal impediments to a more widespread use of diversity in agriculture. While technical solutions can and will be found relatively easily, possibly the most important impediment to the use of functional diversity is the lack of diversified varieties and the associated legal problems.

Clearly, breeders must be rewarded for their work and one way is through royalties. However, the current legal situation in all member countries of the Union for the Protection of New Varieties (UPOV) prevents the inclusion of functional genetic diversity for disease, pest, and other abiotic stress resistances into population varieties. In addition, it does not allow for the deliberate production of population varieties where pure lines are the standard. There is a need to find new solutions that will allow breeders to be compensated for their efforts without constraining the potential for improving yield stability and the durability of disease and pest resistance in practical agriculture through intra-crop diversity. There is also a need for breeding crops adapted to mixed cropping, and technological solutions need to be found to allow farmers to efficiently increase systems diversity in agriculture.

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