African Journal of Agricultural Research Vol. 6 (33), pp. 6780-6789, 30 December, 2011
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJARX11.047
ISSN 1991-637X ©2011 Academic Journals

Review

Wheat cultivar blends: A step forward to sustainable agriculture

Javad Faraji

Young Researchers Club, Boroujerd Branch, Islamic Azad University, Boroujerd, Iran. E-mail: javad_f84@yahoo.com.

Accepted 12 December, 2011

It is only in the last hundred years or so that crop monoculture has become predominant in industrialized agriculture for field and plantation crops. The reasons were for simplicity of planting, harvesting and other operations, which could all be mechanized, and for uniform quality of the crop product. However, monoculture produced severe disadvantages, such as vulnerability to diseases, pests and weeds, and yield instability, which necessitated, for example, the large-scale use of pesticides, fertilizers and growth regulators. To avoid or reduce some of the problems of monoculture, we need to introduce and manage diversity in better ways. At the highest level, species monoculture is difficult to change, at least in the short term. At the variety level, diversification is easy to manage, in the form of variety mixtures within the field. The idea of purposely blending different varieties of wheat is more than 50 years old and was first proposed and tested to reduce the impact of stem and leaf rust. More recently, this concept has also been expanded to look whether blends improved grain yield and/or grain quality. This article reviews the current knowledge about the mechanisms that account for disease reduction and yield increase in a variety of mixtures. It discusses the various determinants in the adoption of a variety of mixtures and the prospects for and challenges in using a variety of mixtures as a functional diversification strategy.

Key words: Disease reduction, diversity, sustainable agriculture, wheat variety mixtures, yield stability.

INTRODUCTION

Wheat variety blends are seed mixtures of two or more pure varieties. Cultivar mixtures refer to mixtures of cultivated varieties growing simultaneously on the same parcel of land with no attempt to breed for phenotypic uniformity (Mundt, 2002). Wolfe (1985) defined cultivar mixtures as mixtures of cultivars that vary for many characters including disease resistance, but have sufficient similarity to be grown together. Compared to the modern monoculture model, blending wheat varieties is a different approach. Each wheat variety has susceptibilities that can cause fluctuations in yield. For example, some varieties are highly disease resistant but may respond poorly to drought or a variety that is fairly cold-hardy may succumb to certain insect pests. In any environment where stresses occur unpredictably, combining pure varieties that have complementary strengths can help stabilize yields (Cowger, 2007). Variety and species mixtures are not only being used extensively in small-scale subsistence agriculture worldwide but also in large-scale systems. Cultivar blends have been used extensively in small grain production in several European countries (Wolfe, 2001). Currently, 6 to 15% of the wheat production area in the states of Washington, Oregon, and Kansas is planted to blends every year (NASS, 2007). Approximately 17% of the 644 000 ha of soft white common winter wheat seeded in Washington in 1999 consisted of mixtures (WASS, 1999).

Part of the mixture production is for animal feed; however, cereal cultivar mixtures in Switzerland, Poland and the US are used for bread and beer production. Most interesting is the fact that the highest quality coffee of Colombia is almost all produced in cultivar mixtures to protect the coffee from the coffee rust disease. These mixtures are perennial and have been successful since 1982 on a large scale (Wolfe, 2001). Superiority of cultivar blends over pure-line cultivars have been observed in numerous crops, including wheat (Banziger et al., 2010; You-Yong et al., 2009; Cowger and Weiz, 2008; Pridham and Entz, 2005; Bowden et al., 2001), soybean (Biabani et al., 2008), forage maize (Afonin and Stepanku, 1996), barley (Jokinen, 1991; Valentine, 1982), flax (Gubbles and Kenachuk, 1987) and cotton (Bechere, 2008). Cultivar mixtures have been suggested as a means to achieve increased crop productivity. By choosing cultivars that complement each other for performance of important traits, mixtures could be formulated to meet specific production requirements. Main advantages reported for blends are yield increase (Gallandt et al., 2000), yield stability across diverse environments (Østergård et al., 2005; Kaut et al., 2006), more efficient use of limited growth resources (Biabani, 2009), better control of pest (Cox et al., 2004), diseases (Ngugi et al., 2001) and weeds (Rodri'guez, 2006).

Other potential benefits of using blends include overcoming winter injury by tiller compensation (Bowden et al., 2001), spreading out periods of nutrient and water requirement (Tilahun, 1995), compensation for neighboring plants killed or weakened by environmental stress (Essah and Stoskopf, 2001) and decreased lodging (Newton et al., 2002; Mundt, 2002; Stützel and Aufhammer, 1988; Grafius, 1966). Superiority of cultivar blends over pure stands attributed to blends component differences in some agronomic characteristics such as height (Trenbath, 1974) and maturity (Schweitzer, 1986). Despite numerous examples in which mixture performance was superior to that of pure line components, there are exceptions. Rajeswara and Prasad (1982) compared grain yield of spring wheat mixtures and their pure line components, and found no advantage of mixtures.

Likewise, Finckh and Mundt (1996) examined mixtures of five winter wheat varieties in Oregon and found that yield did not differ between mixtures and pure lines. Baker and Briggs (1984) found no significant differences in yield between the average performance of 10 barley cultivars and the 45 possible two-component mixtures. Patterson et al. (1963) found no yield advantage of oat mixtures over pure line components, but noted that mixtures had greater lodging resistance.

Yield stability

Yield stability is one of the main benefits reported for blends. Cultivar mixtures can have a higher yield and more yield stability than pure stands of the components (Finckh et al., 2000). Smithson and Lenne (1996) summarized the yield results from more than 100 studies of intraspecific field crop blends, and concluded that on average blend yields exceeded their midcomponents by a small but significant amount, and the advantage was greater for wheat (5.4%) than other field crops. Jensen (1988) summarized literature concerning mixtures and concluded that the grain yield of mixtures was generally close to the average of the components, with a small skew towards the higher-yielding component. He suggested the most appropriate uses of mixtures would be to (i) identify the occasional mixture that performed better than the best component, and (ii) utilize other benefits of mixtures such as lodging resistance, stability, or specialty use.

Likewise, Trenbath (1974), in an extensive review of literature in which forage yield of mixtures was measured, found that yield of mixtures was greater than that of pure lines in more than half the experiments examined. A growing number of studies show that in natural ecosystems, functional diversity leads to higher stability (Petchey and Gaston, 2002). Such functional diversification can be achieved by using cultivar mixtures (Wolfe, 1985). Smithson and Lenne (1996) analyzed 35 data sets of yields of blends and their components for genotype x environment interaction, using analysis of variance and regression, and concluded that blend yields almost always varied less among environments than did the yields of blend components. Østergård et al. (2005) grew six three-component spring barley (*Hordeum vulgare* L.) blends and their components in 17 environments, and found that blends were on average more stable than pure cultivars both in actual yield and in yield ranking.

Published results from field trials of cereal variety mixtures demonstrate, however, both positive and negative effects on grain yield. To investigate the prevalence and preconditions for positive mixing effects, reported grain yields of variety mixtures and pure variety stands were obtained from previously published variety trials, converted into relative mixing effects and combined using meta-analysis. Twenty-six published studies, examining a total of 246 instances of a variety of mixtures of wheat (*Triticum aestivum* L.) and barley (*H. vulgare* L.), were identified as meeting the criteria for inclusion in the meta-analysis; on the other hand, nearly 200 studies were discarded. The accepted studies reported results on both winter and spring types of each crop species. Relative mixing effects ranged from −30 to 100% with an overall meta-estimate of at least 2.7% ($P < 0.001$), reconfirming the potential of overall grain yield increase when growing varieties in mixtures. The mixing effect varied between crop types, with largest and significant effects for winter wheat and spring barley. The meta-regression demonstrated that mixing effect increased significantly with:

1. Diversity in reported grain yields,
2. Diversity in disease resistance, and
3. Diversity in weed suppressiveness, all among component varieties.

Relative mixing effect was also found to increase significantly with the effective number of component varieties (Kiær et al., 2009).

Number of cultivar in blends

The effect of different numbers of blend components has been studied, and the evidence on whether increased component number correlates with yield improvement is mixed (Smithson and Lenne, 1996). In at least three studies of small grains, blend yield advantages were greater with more than two components than with just two (Newton et al., 1997; Nitzsche and Hesselbach, 1983; Stuke and Fehrmann, 1987). Nitzsche and Hesselbach (1983) studied blends of spring barley and reported that yield increased as the number of components in the blends increased from two to six. Smithson and Lenne (1996) reported that yield stability of field crop blends improved with increasing numbers of components in about half the datasets they examined. The number of cultivars in the mixture can influence the disease control benefit achieved from it. Mundt (1994) showed that increasing the number of cultivars up to 5 gave a trend towards decreasing the severity of stripe rust on wheat, but with potentially diminishing returns beyond 3 or 4 cultivar components. Newton et al. (1997) obtained similar results in the control of scald on winter barley.

Diversity in cultivar blends

An important prerequisite in using mixtures is the diversity of cultivars to be included in terms of agronomic traits (Castilla et al., 2003). There may be a relationship between component diversity and blend advantage, although the evidence is not uniform (Smithson and Lenne, 1996). Some studies of soybean blends with components divergent in yield, plant height, and/or maturity have shown a positive relationship between mixture advantage and component diversity (Mumaw and Weber, 1957; Schweitzer et al., 1986; Smithson and Lenne, 1996). In contrast, some studies showed no relationship between mixture advantage and maturity differences in soybean cultivars (Patterson et al., 1963; Gizlice et al., 1989). One of the main reasons behind the superiority of wheat cultivar blends over sole cultivars may be attributed to the differences among cultivar's height. Such differences can result in creating a wavy canopy in the field, which consist of a combination of shorter and taller cultivars beside each other. This structure can leads to more uniform distribution of leaves, more penetration of light into the canopy due to decreased shading of adjacent plants on each other and subsequently less inter-species competition among plants for receiving light.

In this case, absorbed energy by plants allocates to dry matter accumulation instead of more vegetative growth. Moreover, we have limitations for increasing plant densities particularly under dryland conditions due to soil moisture deficiency. However, without any change in plant populations in a wavy canopy, more photosynthetic parts are exposed to the light because of increased light use efficiency, which leads to increasing photosynthesis and dry matter production as well as optimum utilization of limited soil moisture content. Additionally, if the light passes by taller cultivar, shorter cultivar can absorb the light and increases light use efficiency. Increased light use efficiency in cultivar blends not only is responsible for increasing photosynthesis and dry matter production but also results in lesser evaporation from the soil surface by reducing amounts of the light reaching the soil surface and help to preserving soil water content which is absolutely necessary for producing optimum yields specially in rainfed farming (Faraji, 2011). Height variability in spring wheat (*T. aestivum* L.) cultivars permits growing them in systematic mixed stands and such mixtures are reported to lead to better utilization of solar radiation.

Studies on such wheat mixtures are limited (Prasad and Sharma, 1980). Essah and Stoskopf (2001) blended barley cultivars that varied in stature and maturity, and found a yield advantage to blending early with late cultivars, as long as the maturity difference was not too great. They hypothesized that the early:late combination allowed the plants to maximally exploit their environment. The conflicting results among previous experiments demonstrate that relationship between diversity and blend performance may vary according to the species investigated, the sample of cultivars, or the environments in which they were tested (Helland and Holland, 2003).

Agronomic considerations

With regard to cultivar mixtures, a basic question concerns whether increased genetic diversity among the individual crop plants is compatible with the production and marketing goals of the production system. Genotype and species mixtures are common in traditional agriculture. Current evidence also suggests that mixtures can work in commercial and modern agriculture (Mundt, 1994; Bowden et al., 2001). Marketing restrictions and processing quality are often cited as major limitations to the use of mixtures. However, cultivars of the same market class are often bulked during handling and shipping. The German experience with barley demonstrated that adequate malting quality could be maintained in the face of widespread deployment of cultivars mixtures (Wolfe, 1992). Individual blends may have positive, neutral, or negative effects on yield, and thus blends must be tested under varying conditions before recommendations can be made (Mundt et al., 1995 a, b).

It would be desirable to plant blends in small unit areas, to screen the largest possible number of component combinations each year. A system for mixing cultivars must be designed to minimize anticipated difficulties in crop establishment, harvesting, and milling and marketing of grains that are usually associated with the adoption of cultivar mixtures. It is also important to quantify the costs and benefits to determine whether the benefits, such as those derived from the increase in yield and reduction in fungicide use, can offset additional costs (Leung et al., 2003). In order to weigh these advantages and disadvantages, producers must know how blends actually perform in the field. Because innumerable combinations of varieties are possible, performance testing of all blends is not feasible (Bowden et al., 2001).

Relations between land size and efficiency of cultivar blends

Cowger and Weisz (2008) examined the effects of two different plot sizes (6.1×3.1 and 1.83×0.31 m) on performance of wheat cultivar blends and reported small plots did not demonstrate a blend advantage, while nearby large plots did. The factors contributing to the overall blend advantage in the larger plots, such as disease reduction and compensation, evidently had lesser effects in the smaller plots. This result is consistent with the findings of other researchers (Mille et al., 2006; Wolfe, 1985; Zhu et al., 2000). Blend benefits are probably greater at larger spatial scales, as host-diversity effects on disease may increase over larger areas (Garrett and Mundt, 1999). This is due in part to the fact that, at least for some wind-dispersed foliar diseases, the velocity of disease expansion increases with distance from inoculum source (Cowger et al., 2005; Ferrandino, 1993).

Thus, the difference in epidemic velocity between pure and mixed stands will become greater over larger distances, giving an increased host-diversity advantage at larger spatial scales. An increasing blend advantage at larger spatial scales has been observed experimentally (Mille et al., 2006; Wolfe, 1985; Zhu et al., 2000). It suggests that blend efficacy must be evaluated at some minimum plot size, and blends found to be advantageous at that scale should also be tested over larger areas.

Contribution of bio-diversity to food security

Some of the most profound and direct impacts of climate change over the next few decades will be on agriculture and food systems (Brown and Funk, 2008). Increasing temperatures, declining and more unpredictable rainfall, more frequent extreme weather and higher severity of pest and disease are among the more drastic changes that would impact food production (Parry et al., 2007; Morton, 2007; Lobell et al., 2008). Farmers in poorer countries with harsh climate conditions will likely be most affected. It has been shown that by 2080, the 40 poorest countries, located predominately in tropical Africa and Latin America, could lose 10 to 20% of their basic grain growing capacity due to drought (Kotschi, 2007). A review of recent scientific literature underlines that the most effective strategy to adopt agriculture to climate changes is to increase biodiversity. A mix of different varieties in one filed is a proven and highly reliable farming method to increase stress tolerance to erratic weather changes. Diversity farming is the single most important modern technology to achieve food security in a changing climate. Scientists have shown that that diversity provides a natural insurance policy against major ecosystem changes, be it in the wild or in agriculture (McNaughton, 1977; Chapin et al., 2000; Diaz et al., 2006). It is now predicted that genetic diversity will be most crucial in highly variable environments and those under rapid human-induced climate change (Reusch et al., 2005; Hajjar et al., 2008; Hughes et al., 2008).

The larger the number of different species or varieties presents in one field or in an ecosystem, the greater the probability that at least some of them can cope with changing conditions. Species diversity also reduces the probability of pests and diseases by diluting the viability of their hosts (Chapin et al., 2000). It is an age-old insurance policy of farming communities to hedge their risks and plant diverse crops. The strategy is not to maximize yield in an optimum year, but to maximize yield over years, good and bad, by decreasing the chance of crop failure in a bad year (Altieri, 1990). This diversification strategy is backed by a wealth of recent scientific data. In a unique cooperation project among Chinese Scientist and farmers in Yunnan during 1998 and 1999, researchers calculated the effect of diversity on the severity of rice blast, the major disease of rice (Zhu et al., 2000). They showed that disease-susceptible rice varieties planted with resistant varieties had an 89 percent greater yield than when they were grown in a monoculture. Mixed varieties of rice produced more grain per hectare than their corresponding monocultures in all cases. The experiment was so successful that fungicidal sprays were no longer applied by the end of the two-year program. This is especially remarkable as the yield gains were on top of already high average yields in the region, at nearly 10 tones per hectare, among the highest in the world (Zhu et al., 2000). This shows that greater rice diversity means lower rates of plant disease and greater yields while conserving genetic diversity, all at minimal cost for farmers and the environment. In another example in Italy, a high level of genetic diversity within wheat fields on non-irrigated farms reduces risk of crop failure during dry conditions. A scenario where rainfall declines by 20%, the wheat yield would fall sharply, but when diversity is increased by 2%, this decline can not only be reversed but above average yields achieved (DiFalco and Chavas, 2006, 2008). Off the German coast, a genetically diverse area of seagrass was not only able to survive a heat wave, but experienced 26 to 34% more growth than seagrass monocultures, showing how genetic diversity increases the ability for plants to recover after a perturbation, while genetic monocultures have a limited short-term ability to respond to extreme climatic events (Reusch et al., 2005).

There is abundant scientific evidence that crop biodiversity has an important role to play in the adaptation to our changing environment. While oversimplified farming systems, such as monocultures of genetically identical plants, would not be able to cope with a changing climate, increasing the biodiversity of an agro-ecosystem can help maintain its long-term productivity and contribute significantly to food security. Genetic diversity within a field provides a buffer against losses caused by environmental change, pest and diseases. Genetic diversity provides the resilience needed for a reliable and stable, long-term food production (Diaz et al., 2006).

Analysis of past environment changes that resulted in dramatic famines (Ireland's potato famine and Ethiopia, 1965 to 1997) shows specialized monocultures are highly vulnerable (Fraser, 2007). In addition to enhancing food security and climate resilience, diversity in the field also delivers important ecosystem services. Variety mixtures that are tolerant to drought and flood not only increase productivity, but also prevent soil erosion and desertification, increase soil organic matter and help stabilize slopes (Hajjar et al., 2008). Benefits for farmers include reducing the need for costly pesticides, receiving price premiums for valued traditional varieties and improving their dietary diversity and health (Hajjar et al., 2008). Bio-diverse farming is a proven, effective strategy to adapt to climate change.

Through it, we can create farms that are able to maintain and increase food production in the face of increasingly unpredictable conditions. Agriculture will not only be affected by climate change, it is a substantial contributor to greenhouse gas emissions. By reducing agriculture's greenhouse gas emissions and by using farming techniques that increases soil carbon, farming itself can contribute to mitigating climate change (Bellarby et al., 2007).

In fact, many bio-diverse farming systems are both mitigation and adaptation strategies, as they increase soil carbon and use cropping systems that are more resilient to extreme weather. In order to increase our food security in a changing world, policy makers need to invest more in modern and effective bio-diverse farming systems. A one-sided focus on GE plants contradicts all scientific findings on climate change adaptation in agriculture, and is a long-term threat to global food security.

Quality factors in cultivar blends

It is well known that the bread-making quality of wheat is much related to the protein content in grain (Kadziulien et al., 2009). Variation in protein concentration due to environmental conditions has been reported in previous studies of hard white wheat cultivars (Huang and Varriano-Marston, 1980; McGuire et al., 1994; Lang et al., 1998). Grain protein concentration of hard white wheat is a crucial factor in determining noodle, bread, and tortilla quality (McGuire et al., 1994; Qarooni et al., 1994; Lang et al., 1998; Wang and Flores, 1999; Ambalamaatil et al., 2002). Typically, hard white wheat cultivars and their blends have shown good bread-making performance (Bean et al., 1990; Chang and Chambers, 1992; Morris, 1992; McGuire et al., 1994; Lang et al., 1998; Campbell et al., 2001; Ambalamaatil et al., 2002; Habernicht et al., 2002). Blending hard white wheat cultivars represents a sound strategy to stabilize yield and end-use quality (Lee et al., 2005). It has been recognized that the grain lot mixtures of hard white and hard red wheats and the grain lot mixtures of hard white and soft white wheats could affect processing quality and end-use performance (Bequette and Herrman, 1994; Habernicht et al., 2002).

Bean et al. (1990) showed a synergistic improvement in bread quality by blending low protein ‘Klasic’ and low protein ‘Anza’ flours in equal portion. Morris (1992) evaluated the blending of three grain lots of Klasic with two popular soft white wheat cultivars (Daws and Stephens) to assess the potential impact of mixing white wheat classes on hard wheat milling and baking quality. Blending changed quality in one of two ways:

1. A linear response proportional to the relative amount of each component in a blend with the quality of the blend intermediate between the quality of the unblended grain lots and
2. A curvilinear response in which a small amount (e.g., 10%) of soft wheat had a disproportionally large effect.

No synergistic effects due to blending were observed. A linear response pattern was observed for grain test weight, near-infrared reflectance (NIR) hardness score, and protein and for flour yield, protein, and water absorption. Traits that followed a curvilinear response pattern included dough mixing time and straight-dough pan-bread volume.

Faraji (2011) evaluated three two-component wheat cultivar blends at five blending ratios and three different seeding rates and concluded in over all, although there were no significant differences between sole cultivars and cultivar blends regarding grain quality factors but the results revealed that the highest protein content and water absorption indices were obtained in cultivar blends. Increased water absorption represents value to bakers because they add more water to the flour, thus increasing product yield and shelf-life (Lee et al., 2005).

Flour water absorption is an important character that is highly associated with the quality of bread, tortillas, and noodles (Qarooni et al., 1994; Lang et al., 1998; McGuire et al., 1994). Cowger and Weisz (2008) studied the performance of eight soft red winter wheat cultivars having a range of maturities with that of 13 blends, each consisting of equal proportions of two or three of the cultivars in 3 locations in North Carolina. They reported that in general, blends did not differ significantly from midcomponents for test weight, protein content, hardness and falling number.

Mechanisms for increasing yield and yield stability in cultivar blends

Complementary effect

All varieties have some weaknesses that cause fluctuations in yield. A variety might be very susceptible to a disease or insect, it might respond poorly to drought stress, or it might be prone to winter injury. Combining several different varieties with complementary strengths is a way to reduce the yield fluctuations associated with any particular variety (Bowden et al., 2001). The yield benefit of cultivar mixtures may be a function of complementary resource use above and below ground (Willey, 1979). As in interspecific mixtures, a yield advantage occurs when cultivar components differ in their use of resources in space and time in such a way that overall use of resources is better than when components are grown separately.

Complementary effect usually occurs when component cultivars have different growth durations because the demand on resources occurs at different times (Fukai and Trenbath, 1993). Grain yield in mixtures is influenced by intraspecific competition between component pure lines that begins during early development and continues to physiological maturity. Apparently, complementary relationships among pure lines in mixtures for growth habit, shading, or other factors were responsible for the increased grain yield of mixtures (Gallandt et al., 2001).

Compensation

A strong variety may be able to compensate for a weak or injured variety by producing more tillers, bigger heads, or heavier kernels. This effect operates only between neighboring plants, so it cannot occur when varieties are grown in separate fields. Blending varieties with different genetic backgrounds should increase the chances of compensation (Bowden et al., 2001). Compensation usually happens between cultivars with different competitive abilities (Willey, 1979). It occurs when the yield of one component increases, while the other decreases without affecting the overall yield of the mixture (Khalifa and Qualset, 1974). Compensatory tillering by resistant plants was observed when disease occurred early in the season (Brophy and Mundt, 1991) and even in mixtures where disease intensity was not affected (Mundt et al., 1995a).

Compensation was also observed in cultivar mixtures where the components differed in plant height (Khalifa and Qualset, 1974). A model is presented explaining those mixing effects in cereal cultivar blends that cannot be attributed to reduced disease levels but are thought to result from improved compensatory reactions to environmental stress in cereal cultivar blends. It is assumed that a cultivar which yields less than expected in a particular environment does not utilize all growth factors available. The amount of growth factors not utilized is postulated to be taken up by the other mixture component which then produces more than expected in pure stand. It is hypothesized that this additional ‘compensatory’ yield is what is usually named the mixing effect (Stützel and Aufhammer, 1990).

Facilitation

Facilitation is the positive effect of plants on the establishment or growth of other plants (Garcia-Barrios, 2002). A component cultivar may benefit another component directly by improving microclimate, providing physical support or windbreaks, and ameliorating harsh environmental conditions, or indirectly by providing protection from other pests and diseases, and improving water-holding capacity (Callaway, 1995; Garcia-Barrios, 2002). Although rarely quantified, a form of facilitation observed in rice cultivar mixtures is the higher resistance to lodging of tall cultivars in mixtures than in monoculture (Castilla et al., 2003).

Mechanisms for reducing epidemics in cultivar blends

Dilution effect

Disease is reduced in cultivar mixtures because of the increased distance between plants of the susceptible cultivar in the mixture (Browning and Frey, 1969; Chin and Wolfe, 1984). In cultivar blends, the susceptible members are farther apart than in a pure stand, so a dilution effect may occur as diseases or pests are transported between susceptible plants (Bowden et al., 2001). In fact, the presence of the resistant cultivar decreases the chance of the inoculum produced from the infected susceptible cultivar of landing on another susceptible cultivar. Most of the inoculum lands on the resistant cultivar, thus reducing the rate of disease increase.

Barrier effect

For any particular disease or pest, the resistant members of the blend may shield the susceptible members from spread within the crop canopy (Bowden et al., 2001). The resistant cultivar provides a physical barrier that restricts the movement of the inoculum from the susceptible cultivar (Browning and Frey, 1969). For mixtures of differentially susceptible cultivars (that is both components are susceptible to different races of the pathogen), plants of cultivar A serve as a barrier for the race that attacks cultivar B, and vice versa. For barley powdery mildew, Chin and Wolfe (1984) demonstrated that the increased distance between plants of the same genotype in cultivar mixtures was the most important mechanism of control, especially early in the epidemic. The ideal spatial arrangement of host genotypes is one in which plants susceptible to the same pathogen race do not occur as neighbors.

Induced resistance

This occurs when races that are nonvirulent on a cultivar induce the plant's defense response mechanisms. As a consequence, any virulent race (genetically different isolate of the same pathogen that would normally infect the plant) invading exactly the same area of the plant cannot cause infection (Chin and Wolfe, 1984). This induction of defense responses reduces partially the susceptibility of the host plant to infection by spores of a virulent strain or race (Lannou et al., 1995). Either the infection efficacy or the number of new spores produced as a result of infection can be reduced (Martinelli et al., 1993). Experimental studies indicate that induced resistance may account for 20 to 40% of the disease reduction in mixtures when two or more pathogen races are active in the crop (Lannou and de Vallavieille-Pope, 1997). According to Calonnec et al. (1996), up to one third of the reduction in infection by *Puccinia striiformis* in wheat mixtures was due to induced resistance.

Competition among pathogen races

The diversity of pathogen genotypes is expected to be higher in cultivar mixtures than in monoculture, thus increasing the chance of interactions and competition between pathogen races (Garrett and Mundt, 1999). Competition among different virulent races may prevent a certain race from dominating and over- coming host resistance in cultivar mixtures, thus reducing disease in the mixtures.

Potential disadvantages

Potential disadvantages of mixing cultivars also need to be considered. Mixing the seed is a major disadvantage with blends because of the added time and cost involved in mixing. Many producers do not have the grain handling equipment to do this easily. Also, because the proportions of a blend likely will shift during each growing season, producers might need to remix blends annually, further adding to the time and cost involved. Another potential disadvantage is variety incompatibility.

If early and late varieties are blended, the early varieties may shatter before the late varieties are ready to harvest. If tall and short varieties are mixed, too much straw may be forced through the combine at harvest. The third potential disadvantage is the lost opportunity to manage varieties separately. If varieties are grown in separate fields, a variety with winter injury can be torn up and planted to a summer crop. If all fields are planted with blends, the injured variety cannot be eliminated. Segregating high protein grain to capture quality premiums would also be more difficult with blends. Likewise, producers often spread their harvest dates by planting varieties with different maturities. That may be harder to achieve with blends (Bowden et al., 2001).

Conclusion

While modern agriculture has brought vast increases in productivity to the world's farming systems, it is widely recognized that much of this may have come at the price of sustainability. Most practices of modern agriculture, e.g. mechanization, monocultures, improved crop varieties, and heavy use of agrochemicals for fertilization and pest management, led to a simplification of the components of agricultural systems and to a loss of biodiversity. Restoring on-farm biodiversity through diversified farming systems that mimic nature is considered to be a key strategy for sustainable agriculture.

In stress-prone regions where environmental stresses such as limited and erratic rainfalls, severe temperature fluctuations during growing season, late-season drought associated with high temperatures during grain filling period, freezing temperatures during winter as well as disease outbreak and pest infestation occur frequently, combining cultivars that have complementary characteristics may reduces risks of crop failure and increases yield stability. Compared with many other 'environmentally friendly' approaches, use of variety mixtures is likely to have a far greater beneficial effect on the environment as it could be readily adopted for use over a large proportion of cereal growing areas of the world.

REFERENCES

Afonin MM, Stepantsov VO (1996). Growing mixtures of hybrids differing in earliness. Kukuruza I Sorgo, 4: 5-6.

Altieri MA (1990). Agroecology. In: Agroecology (eds Carrol, C.R., Vandermeer, J.H. and Rosset, P.M.) McGraw Hill, New York, pp. 551-564.

Ambalamaatil S, Lukow OM, Hatcher DW, Dexter JE, Malcolmson LJ, Watts BM (2002). Milling and quality evaluation of Canadian hard white spring wheats. Cereal Foods World, 47: 319-327.

Baenziger PS, Nelson LA, Mengistu N, Eskridge KM, Klein RN, Baltensperger DD, Elmore RW (2010). Grain Yield Performance and Stability of Cultivar Blends vs. Component Cultivars of Hard Winter Wheat in Nebraska, Published. Crop Sci., 50: 617-623.

Baker RJ (1984). Comparison of grain yield of uniblends and biblends of 10 spring barley cultivars: –87. Crop Sci., 24: 85-87.

Bean MM, Huang DS, Miller RE (1990). Some wheat and flour properties of Klasic: A hard white wheat. Cereal Chem., 67: 307-309.

Becher E, Alexander A, Auld DL, Downer CP (2008). Effect of cultivar blends on fiber quality, lint yield and gross return of upland cotton in west texas. J. Cotton Sci., 12: 8-15.

Bellarby J, Foereid B, Hastings A, Smith P (2007). Cool farming: climate impacts of agriculture and mitigation potential. Greenpeace international, The Netherlands. http://www.greenpeace.org/international/press/reports/cool-farming-full-report.

Bequette RK, Herrman TJ (1994). Hard white wheat. Kansas State Univ. Coop. Ext. Ser. MF1111, Manhattan, KS.

Biabani A (2009). Agronomic performance of intercropped wheat cultivars. Asian J. Plant Sci., 8(1): 78-81.

Biabani A, Hashemi M, Herbert SJ (2008). Agronomic performance of two intercropped soybean cultivars. Plant Prod., 2(3): 215-222.

Bowden R, Shoyer J, Roozeboom K, Claasen M, Evans P, Gordon B, Heer B, Janssen K, Long J, Martin J, Schlegel A, Sears R, Witt M (2001). Performance of wheat variety blends in Kansas. Kansas State University Agric. Extension Bull. 128 (www.oznet.ksu.edu/library/crpsl2/SRL128.pdf).

Brophy LS, Mundt C (1991). Influence of plant spatial patterns on disease dynamics, plant competition and grain yield in genetically diverse wheat populations. Agric. Ecosyst. Environ., 35: 1-12.

Brown ME, Funk CC (2008). Food security under climate change. Science, 319: 580-581.

Browning JA, Frey KJ (1969). Multiline cultivars as a means of disease control. Annu. Rev. Phytopathol., 14: 355-382.

Callaway RM (1995). Positive interactions among plants. Bot. Rev., 61: 306-349.

Calonnec A, Goyeau H, De Vallavieille-Pope C (1996). Effects of induced resistance on infection efficiency and sporulation of *Puccinia striiformis* on seedlings in varietal mixtures and on field epidemics in pure stands. Eur. J. Plant Pathol., 102: 733-741.

Campbell KG, Finney PL, Bergman CJ, Gualberto DG, Anderson JA, Giroux MJ, Siritunga D, Zhu J, Gendre F, Roue C, Verel A, Sorrells ME (2001). Quantitative trait loci associated with milling and baking quality in a soft × hard wheat cross. Crop Sci., 41: 1275-1285.

Castilla NP, Versa Cruz CM, Mew TW, Zhu Y (2003). Using rice cultivar mixtures: a sustainable approach for managing diseases and increasing yield. Mini review. The Phytopathology Laboratory of Yunnan Province, Yunnan Agricultural University, Kunming.Yunnan 650201, China.

Castro A (2001). Cultivar Mixtures. The Plant Health Instructor. DOI: 10.1094/PHI-A-2001-1230-01.

Chang CY, Chambers IV E (1992). Flavor characterization of breads made from hard red winter wheat and hard white winter wheat. Cereal Chem., 69: 556-559.

Chapin FS, Zavaleta ES, Eviner VT, Naylor RL, Vitousek PM, Reynolds HL, Hooper DU, Lavorel S, Sala OE, Hobbie SE, Mack MC, Diaz S (2000). Consequences of changing biodiversity. Nature, 405: 234-242.

Chin KM, Wolfe MS (1984). Selection on Erysiphe graminis in pure and mixed stands of barley. Plant Pathol., 33: 535-546.

Cowger C (2007). Blended Wheat Varieties Show Their Strength. May/June 2007 issue of *Agricultural Research* magazine.

Cowger C, Wallace LD, Mundt CC (2005). Velocity of spread of wheat stripe rust epidemics. Phytopathology, 95: 972-982.

Cowger C, Weisz R (2008). Winter Wheat Blends (Mixtures) Produce a Yield Advantage in North Carolina. Agron. J., 100(1): 169-177.

Cox CM, Garret KA, Bowden RL, Fritz AK, Dendy SP, Heer WF (2004). Cultivar mixtures for the simultaneous management of multiple diseases: tan spot and leaf rust of wheat. Phytopathology, 94: 961-969.

Di Falco S, Chavas Jp (2006). Crop genetic diversity, farm productivity and the management of environment risk in rainfed agriculture. Eur. Rev. Agric. Econ., 33: 289-314.

Di Falco S, Chavas Jp (2008). Rainfall shocks, resilience, and the effects of crop biodiversity on agroecosystem productivity. Land Econ., 84: 83-96.

Diaz S, Fargione J, Chapi FS, Tilman D (2006). Biodiversity loss threatens human well-being. PLoS Biol., 4: 1300-1306.

Essah SYC, Stoskopf NC (2001). Mixture performance of phenotypically contrasting barley cultivars. Can. J. Plant Sci., 82: 1-6.

Faraji J (2011). Evaluating the effects of cultivar blends and plant density on some quantitative and qualitative characteristics of three bread wheat cultivars under dryland conditions, M.S thesis on agronomy, Faculty of post graduation– Department of Agriculture, Islamic Azad University, Boroujerd Branch, Iran.

Ferrandino FJ (1993). Dispersive epidemic waves: I. Focus expansion within a linear planting. Phytopathology, 83: 795-802.

Finckh MR (1996). Temporal dynamics of plant competition in genetically diverse wheat populations in the presence and absence of stripe rust. J. Appl. Ecol., 33: 1041-1052.

Finckh MR, Gacek ES, Goyeau H, Lannou C, Merz U, Mundt CC, Munk L, Nadziak J, Newton AC, Vallavieille-Pope C, Wolfe MS (2000). Cereal variety and species mixtures in practice, with emphasis on disease resistance. Agronomy, 20: 813-837.

Fraser E (2007). Travelling in antique lands: using past famine to develop an adaptability/resilience framework to identify food systems vulnerable to climate change. Clim. Change, 83: 495-514.

Fukai S, Trenbath BR (1993). Processes determining intercrop productivity and yields of component crops. Field Crops Res., 34: 247-271.

Gallandt ER, Dofingb SM, Reisenauerc PE, Donaldsonc E (2000). Diallel Analysis of Cultivar Mixtures in Winter Wheat. Crop Sci., 41: 792-796.

Garcia-Barrios L (2002). Plant-plant interactions in tropical agriculture. In: Vandermeer JH, editor. Tropical agroecosystems. Boca Raton, Florida: CRC Press.

Garrett KA, Mundt CC (1999). Epidemiology in mixed host populations. Phytopathology, 89: 984-990.

Garrett KA, Mundt CC (1999). Epidemiology in mixed host populations. Phytopathology, 89: 984-990.

Gizlice Z, Carter TE, Burton JW (1989). The impact of maturity on blend performance in Group V and Group VII soybean cultivars. Agron. J., 81: 559-562.

Grafius JE (1966). Rate of change of lodging resistance, yield and test weight in varietal mixtures of oats, *Avena sativa* L. Crop Sci., 6: 369-370.

Gubbles GH, Kenachuk ED (1987). Performance of pure and mixed stands of flax cultivars. Can. J. Plant Sci., 67: 267-302.

Habernicht D, Martin JM, Talbert LE (2002). End-use quality of hard red white spring wheat contaminated with grain of contrasting classes. Cereal Chem., 79: 404-407.

Helland SJ, Holland JB (2003). Genome-Wide Genetic Diversity among Components Does Not Cause Cultivar Blend Responses. Crop Sci., 43: 1618-1627.

Hjjar R, Jarvis DI, Gemmill-Herren B (2008). The utility of crop genetic diversity in maintaining ecosystem services. Agric. Ecosyst. Environ., 123: 261-270.

Huang G, Varriano-Marston E (1980). α-Amylase activity and preharvest sprouting damage in Kansas hard white wheat. J. Agric. Food Chem., 28: 509-512.

Hughes AR, Inouye BD, Johnson MTJ, Underwood N, Vellend M (2008). Ecological consequences of genetic diversity. Ecol. Lett., 11: 609-623.

Jensen NF (1988). Plant breeding methodology. John Wiley & Sons, New York, NY.

Jokinen K (1991). Yield and competition in barley variety mixtures. J. Agric. Sci. Finland, 63: 287-305.

Kadziulien Z, Sarunaite L, Deveikyte I, Maiksteniene S, Arlauskiene A, Masilionyte L, Cesnuleviciene R, Zekaite V (2009). Qualitative effects of pea and spring cereals intercrop in the organic farming systems. Agron. Res., 7 (Special issue 2): 606-611.

Kaut A, Navabi A, O'Donovan J, Spaner D (2006). Comparing spring wheat cultivar mixtures under conventional and organic management in Alberta. Organic Agriculture Research Symposium – Natural Sciences, 25th Guelph Organic Conference.

Khalifa MA, Qualset CO (1974). Intergenotypic competition between tall and dwarf wheats. I. In mechanical mixtures. Crop Sci., 14: 795-799.

Kiær LP, Skovgaard Ib, Østergård H (2009) Grain yield increase in cereal variety mixtures: A meta-analysis of field trials*.* Field Crops Res.*,* pp. 3-114.

Kotschi J (2007). Agricultural biodiversity is essential for adapting to climate change. GAIA- Ecol. Perspect. Sci. Soc, 6: 98-101.

Lang CE, Lanning SP, Carlson GR, Kushnak GD, Bruckner PL, Tallbert LE (1998). Crop quality and utilization; relationship between baking and noodle quality in hard white spring wheat. Crop Sci., 38: 823-827.

Lannou C, De Vallavieille-Pope C (1997). Mechanisms of variety mixtures for reducing epidemics. In: Variety Mixtures in theory and practice, Wolfe, M. S., ed. European Union Variety and Species Mixtures working group of COST Action 817. Online at: http://www.scri.ac.uk/research/pp/pestanddisease/rhynchosporiumonbarley/otherwork/cropmixtures/varietymixtures

Lannou C, De Vallavieille-Pope C, Goyeau H (1995). Induced resistance in host-mixtures and its effect on disease control in computer-simulated epidemics. Plant Pathol., 44: 478-489.

Lee KM, Shroyerb JP, Herrman TJ, Lingenfelserd J (2005). Blending hard white wheat to improve grain yield and end-use performances. Crop Sci., 46(3): 1124-1129.

Leung H, Zhu Y, Revilla-Molina I, Fan JX, Chen H, Pangga I, Vera Cruz C, Mew TW (2003). Using genetic diversity to achieve sustainable rice disease management. Plant Dis., 87: 1156-1169.

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008). Prioritizing climate change adaptation needs for food security in 2030. Science, 319: 607-610.

Martinelli JA, Brown JKM, Wolfe MS (1993). Effects of barley genotype on induced resistance to powdery mildew. Plant Pathol., 42: 195-202.

McGuire CF, Taylor GA, Rust CH, Kisha TJ (1994). End-use quality of Montana 7811, hard white winter wheat. Montana AgRes. Fall, pp. 9-13.

McNaughton SJ (1977). Diversity and Stability of ecological communities: A comment on the role of empiricism in ecology. Am. Nat., 111: 515-525.

Mille B, Belhaj Fraj M, Monod H, de Vallavieille-Pope C (2006). Assessing four-way mixtures of winter wheat cultivars from the performances of their two-way and individual components. Eur. J. Plant Pathol., 114: 163-173.

Morris CF (1992). Impact of blending hard and soft white wheats on milling and baking quality. Cereal Foods World, 37: 643-648.

Morton JF (2007). Climate change and food Security special feature: the impact of climate change on smallholder and subsistence agriculture. Proc. Nat. Acad. Sci., 104: 19680-19685.

Mumaw CR, Weber CR (1957). Competition and natural selection in soybean varietal mixtures. Agron. J., 59: 154-160.

Mundt CC (1994). Use of host genetic diversity to control cereal diseases: implications for rice blast. In: Rice Blast Disease, Zeigler, R. S., Leong, S. A., and Teng, P. S., eds. CAB International, London, pp. 293-308

Mundt CC (2002). Use of multiline cultivars and cultivar mixtures for disease management. Annu. Rev. Phytopathol., 40: 381-410.

Mundt CC (2002). Use of multiline cultivars and cultivar mixtures for disease management Annu. Rev. Phytopathol., 40: 381-410.

Mundt CC, Brophy LS, Schmitt MS (1995b). Disease severity and yield of pure-line wheat cultivars and mixtures in the presence of eyespot, yellow rust, and their combination. Plant Pathol., 44: 173-182.

Mundt CC, Brophy LS, Schmitt MS (1995a). Choosing crop cultivars and cultivar mixtures under low versus high disease pressure: A case study with wheat. Crop Prot., 14: 509–515.

National Agriculture Statistics Service (2007). US and state data. Available at http://www.nass.usda.gov/index.asp (assessed 1 Apr. 2007; verified 23 Oct. 2007). USDA NASS Washington, DC.

Newton AC, Ellis RP, Hackett CA, Guy DC (1997). The effect of component number on *Rynchosporium secalis* infection and yield in mixtures of winter barley cultivars. Plant Pathol., 45: 930-938.

Newton AC, Guy DC, Nadzik J, Gacek ES (2002). The effect of inoculums pressure, germplasm selection and environment on spring barley cultivar mixtures efficiency. Euphytica, 125: 325-335.

Ngugi HK, King SB, Holt J, Julian M (2001). Simultaneous temporal progress of sorghum anthracnose and leaf blight in crop mixtures with disparate patterns. Phytopathology, 91: 720-729.

Nitzsche W, Hesselbach J (1983). Sortenmischungen statt Viellinien-Sorten 1. Sommergerste. Z. Pflanzenzuecht., 90: 68-74.

Østergård H, Kristensen K, Jensen JW (2005). Stability of variety mixtures of spring barley. In E.T. Lammerts van Bueren et al. (ed.) Proc., Workshop on Organic Plant Breeding Strategies and the Use of Molecular Markers, Driebergen, the Netherlands. Jan. 2005; pp. 17-19

Parry ML, Canziani OF, Palutikof JP, Van der Linden PJ, Hanson CE (2007). Summary for policymakers. In: climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Forth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 7-22.

Patterson F, Schafer J, Caldwell R, Compton L (1963). Comparative standing ability and yield of variety blends of oats. Crop Sci., 3: 558-560.

Petchey OL, Gaston KL (2002). Functional diversity (FD), species richness and community composition. Ecol. Lett., 5: 402-411.

Pridham JC, Entz M (2005). Effect of Intercropping and Cultivar Mixtures on Organic Wheat Production. Presented at the ASA-CSSA-SSSA International Annual Meetings (November 6-10, 2005), Salt Lake City, UT.

Qarooni J, Bequette R, Deyoe C (1994). The performance of U. S. hard white wheats: Effect of milling extraction on flour, pan bread, tortilla and pita (Arabic) bread quality. Lebesm. Wiss. Technol., 27: 270-277.

Rajeswara Rao BR (1982). Studies on productivity of seed blends of two spring wheat cultivars under rainfed conditions. Z. Acker. Pflanzenbau, 151: 17-23.

Reusch TBH, Ehlers A, Hammerli A, Worm B (2005). Ecosystem recovery after climatic extremes enhanced by genotypic diversity. Proc. Nat. Acad. Sci., 102: 2826-2831.

Rodri'guez EE (2006). Effect of cultivar mixture on the competitive ability of barley against weeds. MSc thesis. Institutionen For vaxtproduktionsekologi Sveriges Lantbruksuniversitet.

Schweitzer LE, Nyquist WE, Santini JB, Kimes TM (1986). Soybean cultivar mixtures in a narrow-row noncultivable production system. Crop Sci., 26: 1043-1046.

Smithson JB, Lenne JM (1996). Varietal mixtures: A viable strategy for sustainable productivity in subsistence agriculture. Ann. Appl. Biol., 128: 127–158.

Stuke F, Fehrmann H (1987). Sortenmischungen im Weizenanbau. Nachrchtenbl. Dtsch. Pflanzenschutzdienst, 39: 53-57.

Stützel H, Aufhammer W (1988). Effects of winter barley cultivar mixtures on lodging. J. Agric. Sci., 112: 47-55.

Stützel H, Aufhammer W (1990). The physiological causes of mixing effects in cultivar mixtures: A general hypothesis. Agric. Syst., 32(1): 41-53.

Tilahun A (1995). Yield gain and risk minimization in maize (*Zea mays*) through cultivar mixtures in semi-arid zones of the rift valley in Ethiopia. Exp. Agric., 31(2): 161-168.

Trenbath BR (1974). Biomass productivity of mixtures. Adv. Agron., 26: 177-210.

Valentine J (1982). Variation in monoculture and in mixture for grain yield and other characters in spring barley. Ann. Appl. Biol., 101: 127-141.

Wang L, Flores R (1999). Effect of different wheat classes and their flour milling streams on textural properties of flour tortillas. Cereal Chem., 76: 496-502.

Washington Agricultural Statistics Service (1999). Washington agricultural statistics, 1999. USDA National Agricultural Statistics and Department of Agriculture and Washington State Department of Agriculture, Olympia, WA.

Willey RW (1979). Intercropping – its importance and research needs. Part 1. Competition and yield advantages. Field Crops Abstr., 32: 1-10.

Wolfe MS (1985). The current status and prospects of multiline cultivars and variety mixtures for disease resistance. Annu. Rev. Phytopathol., 23: 251-273.

Wolfe MS (1992). Barley diseases: maintaining the value of our varieties. Pages 1055-1067 in: Barley Genetics Vol. VI, Munk, L., ed. Munksgaard International, Copenhagen.

Wolfe MS (2001). Variety mixtures in theory and practice. Available at www.scri.sari.ac.uk/TiPP/Mix/Booklet/default.htm (assessed 26 June 2007; verified 23 Oct. 2007). Scottish Crop Res. Inst., Invergowrie, Dundee, Scotland.

You-Yong Z, Qi-Cun C, Zhen-Qi L, Yong-Sheng T, Zhen-Sheng K (2009). Effect of wheat cultivar mixtures on wheat yield and stripe rust. Chinese J. Eco-Agric., 17(1): 29-33.

Zhu Y, Chen H, Fan J, Wang Y, Li Y, Chen J, Fan J, Yang S, Hu L, Leung H, Mew TW, Teng PS, Wang Z, Mundt CC (2000). Genetic diversity and disease control in rice. Nature, 406: 718-722.