AGROECOLOGICAL APPROACHES TO BREEDING: CROP, MIXTURE AND SYSTEMS DESIGN FOR IMPROVED FITNESS, SUSTAINABLE INTENSIFICATION, ECOSYSTEM SERVICES, AND FOOD AND NUTRITION SECURITY

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Abstract

Agroecological approaches are designed to attain sustainable food production systems, with enhanced ecosystem function and resource efficiency, drawing from science, practice and social engagement. In addition to good management, the choice of appropriate crop and cultivar for these agroecological targets is essential. Crop and genotype selection must first focus upon agroecological fitness, which requires a close understanding of the desired crop and plant behaviour in order to achieve the productivity, sustainability and ecosystem goals. An important issue is crop design, specifically the traits and trait combinations that confer resource efficiency and ecosystem function, as well as yield and nutritional quality. The dynamics of crop response should also be considered, including patterns of adaptation to different soil constraints or management regimes, and how these patterns may vary with seasonal conditions and climate change. The necessary crop design will differ depending upon these ecosystem and management considerations. These principles can then be adapted to alternative systems, including intercropping, relay sowing and mixtures, based upon the concepts of competition and commensalism. The products that are generated must be considered, whether grain, forage, livestock or all of these, and the associated system evaluated rather than individual efficiencies. Issues for selection in mixed systems are examined with reference to the concepts of co-evolution and joint selection, drawing from diverse examples, including underused and perennial crop forage and tree species. The identification of successful systems will require an improved agroecological understanding as a basis for improved crop, mixture and systems design.

INTRODUCTION

In classic plant breeding (Allard, 1960), plant improvement requires the evaluation of diverse genetic materials for improved adaptation to particular sets of conditions. A diverse set of plants is assembled for evaluation, or additional variability is generated by crossing contrasting lines that possess traits which are desired in combination in the new phenotype. It is essential that the evaluation is conducted in conditions that are representative of the target environment, including its relevant cultural practices (Wade et al., 1996). Improved performance and stability are generally accomplished by first adjusting the growth cycle to better suit the available growing season (Muchow and Bellamy, 1991). Attention is also paid to major biotic and abiotic stresses, so the effective phenotype is stable across the range of conditions that are likely to be encountered (Cooper and Hammer, 1996). The sampling or creation of genetic diversity, followed by its evaluation...
and selection, and the subsequent release of improved phenotypes, is a robust model with wide application. This chapter explores how these principles can be adapted to new plants and more complex systems, such as relay crops, intercrops and mixtures, including pastures and dual-purpose crops for grazing by livestock. The intention is to select adapted phenotypes for agroecological systems that are characterised by the need for sustained or increased yields, improved ecosystem services, more secure farmer livelihoods and better food and nutrition security.

**AGROECOLOGICAL PRINCIPLES FOR MONOCULTURE SYSTEMS**

In all systems resources are finite, so the principle of crop and system design is to capture resources when they are available in order to minimize losses and retain the capacity for continued system function. To do so requires an understanding of the system dynamics, and the tailoring of demand to supply. Therefore, a key issue is the competition for resources and its appropriate phenotypic expression. This is first considered for a pure crop stand (e.g. wheat or barley monoculture), and then the competition model can be adapted to more complex systems.

It is important to recognize that different growing conditions occur early in a breeding programme, where plants are carefully spaced, allowing for the full expression of traits. In comparison, in the actual conditions of a pure crop stand, plant competition and interaction are important factors in plant success. In fact, a different plant type is more successful in spaced nurseries relative to mature swards. This is illustrated by Figure 1, in which three contrasting barley lines are grown in pots as sole plants, or surrounded by two or four close neighbours (i.e. one, three or five plants per pot) (O'Callaghan, 2006). As a spaced single plant, the cultivar Hamelin is able to tiller out better, but when surrounded by four neighbours, the cultivar Yagan is better (Figure 1). Over time these differences become more pronounced (Figure 2), demonstrating differing behaviours, adaptations and competitive abilities.

In pure stands the intent is to minimize interplant competition, so like plants can prosper with their neighbours (Donald, 1951). While the more restricted tillering cultivar may be preferred in that situation, a freely tillering cultivar may be better when weeds are present (Donald, 1968). This is well shown in rice by the cultivar Mahsuri from Malaysia, which is highly competitive due to its large projected leaf area, including a larger than usual flag leaf. Thus, the conditions under which a crop is intended to grow should be a consideration in the breeding programme, such as whether it is for monocropped stands, or to be grown in polyculture.

In considering the improvement of individual crops, it is important to discriminate between the level of investment likely for a major crop, and how it would be possible to make improvements in a new crop or species. For a new crop, the essential principle is to truncate the investment process by foregoing a large formal breeding programme. Initial investment should be used to assemble a diverse set of lines for evaluation, and looking for lines that are better able to perform under the conditions of the test. An example is provided by rice in Cambodia, from which germplasm was lost under the Khmer Rouge regime. Cambodian lines were reintroduced from the world collection, evaluated in the field, and either the reintroduced line or an off-type
Figure 1. Size of leaf area at 39 days for Yagan, Hamelin and Baudin barley grown in a controlled environment room with (A) one, (B) three and (C) five plants per pot

<table>
<thead>
<tr>
<th>LEAF AREA (cm²)</th>
<th>MS</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yagan</td>
<td>50</td>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Hamelin</td>
<td>40</td>
<td>15</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Baudin</td>
<td>30</td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: adapted from O’Callaghan, 2006

Figure 2. Tiller dry weight at 62 days for Yagan, Hamelin and Baudin barley grown in a controlled environment room with (A) one, (B) three and (C) five plants per pot

<table>
<thead>
<tr>
<th>DRY WEIGHT (g)</th>
<th>MS</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yagan</td>
<td>1.4</td>
<td>1.2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Hamelin</td>
<td>1.2</td>
<td>1</td>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>Baudin</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: adapted from O’Callaghan, 2006
(mixture or mutant) was selected and released. Quick gains were possible using this approach, before a full breeding programme including crosses was later developed. Such an approach could be used for potentially promising new crops, such as teff, *Setaria*, other short duration grasses, wild sunflowers, *Lepidium campestre* as an oilseed, bambatse groundnut as a pulse, and many shrub and tree species.

These principles of architectural design from monocultures can be adapted to more complex systems, such as relay crops, intercrops and mixtures, including pastures and dual-purpose crops for grazing by livestock. In doing so, component species can be drawn from annual or perennial species. Recently, efforts have been directed towards developing a suite of perennial crops, which are expected to offer further desirable system alternatives (Wade, 2014), including mixture compatibility, grain and graze opportunities, and system sustainability. In the next section, concepts of architectural design are considered using a variety of examples from Batello *et al.* (2014), the *Proceedings of the FAO Expert Workshop on Perennial Crops for Food Security*. The implications for breeding targets, selection procedures and proof of concept are then discussed.

**AGROECOLOGICAL PRINCIPLES FOR MIXED SYSTEMS**

The advantage of a mixture is that the component species can act at different times or in different zones in order to enhance the effectiveness of resource capture, thereby reducing losses. Furthermore, companion species can be chosen with special attributes to assist effective resource capture, and to ensure delivery of appropriate products for farmers, grazing animals and consumers. For example, on soils of low phosphorus availability, species can be chosen whose roots exude organic acids to mobilize phosphorus. Nitrogen benefits can accrue from the use of legumes for symbiotic nitrogen fixation, or other species with desirable root associations consistent with the enhancement of non-symbiotic nitrogen fixation. Plants such as grasses with deep and extensive root systems can mop-up available nitrate, especially nitrate leached to deeper soil layers. Nutrient acquisition can also be aided by mycorrhizal associations, or by combinations of species which grow in different seasons. An issue that must be considered is the desirability of targeting mutual advantage favouring commensalism over competition. As indicated briefly above, this commensalism can accrue by partners drawing resources from different zones or at different times. Alternatively, there may be biotic benefits via the suppression of pests or encouragement of their parasites and pathogens. The emphasis here is on the selection of compatible plants for mixtures and their associated system benefits. Before doing so, it is worth pursuing examples of these relationships in contrasting systems.

**Case studies of types of mixed systems**

Undisturbed natural systems provide the reference point for long-term system sustainability, in which continuous cover is maintained. In disturbed systems, that scenario is most closely resembled in permanent pasture systems. These systems generally lack formal population structure, with random combinations of perennial and annual species grown in mixed swards,
whose composition varies with resource availability and grazing intensity, as determined by management. Grass–legume pastures are commonly used to combine the nitrogen-fixing benefits of the legume with the nitrogen-responsive attributes of the grass, so that the grazing animal can access improved biomass of higher overall nutritive value (e.g. *Phalaris aquatica*–*Trifolium* spp.; see Figure 3A). Plants included in the pasture can be selected for particular desirable attributes, such as for thrip resistance in the case of gland clover (*Trifolium glanduliferum*), which is illustrated in Figure 3B (Hayes *et al.*, 2014). These pasture systems provide a ground cover and nutrient cycling reference for other disturbed systems.

Figure 3. **Mixed perennial grass–legume pasture**

(A) A mixed forage pasture sward containing a perennial grass (*Phalaris aquatica*) and hard-seeded self-regenerating annual legume species (*Trifolium subterraneum*, *T. michelianum* and *T. glanduliferum*)

(B) Gland clover (*Trifolium glanduliferum*), a self-regenerating annual forage legume released commercially in Australia for its superior insect pest resistance

Source: Hayes *et al.*, 2014

Crop-based systems generally involve structured populations. Here, structure refers to a formal and predictable layout. For example, in a structured population, each species in sown in rows facilitating mechanization, in contrast to random allocation in a polyculture. Structure implies segregation for ease of harvest, but the critical issues are ease of mechanical sowing, inter-row cultivation and harvest.

The extreme case of a structured population is sole-crop monoculture, with the crop sown formally in rows, but preferably at least into stubble from previous cover. This simple system can readily be made more complex by intercropping or relay cropping with other species (Figure 4A), while still retaining structure for ease of management (Bell, 2014). If the annual crop were replaced with a perennial crop such as perennial wheat, the cropping system automatically features at least partial continuous ground cover, which can be further improved by companion or relay sowings of other species such as legumes (Figure 4B). The concept can even be extended to permanent perennial grain crop polyculture (Figure 4C), although the lack of structure may make this complexity more suitable for smallholders, where mechanical harvest is not an issue, and grain can more readily be segregated for marketing.
Generally, some structure can be advantageous, especially in terms of securing effective combinations of productivity and sustainability. An example of phase cropping from southern Australia is presented in Figure 5, showing a diagrammatic representation of resource availability associated with the phase rotation (Bell, 2014). In this example, successive years of the perennial grain utilize soil water and nutrients that are accumulated under a previous pasture phase. That cycle is then replaced, initially by shallow-rooted legumes to restore nitrogen fertility as rainfall recharges the profile. Some water moves past the shallow roots of the annual legume, creating future reserves. Perennial legumes or legume pastures then restore the nutrient and soil water balance before the cycle is repeated. The perennial cereal phase is important in order to capture soil water resources from depth, together with any leached nitrate, in order to avoid the loss of resources past the root zone. This is one structured cropping example of closing the system to ensure balance in resource dynamics and system sustainability.

Figure 5. **Phase perennial crop–annual crop/pasture rotation**

Source: Bell, 2014
Another example involving structured cropping is the doubled-up legume system being adopted in Malawi in southern Africa. Semi-perennial pigeon peas provide intercropping opportunities for farmers. Because of their slow growth rates in the first year, they do not compete aggressively with faster growing legumes such as groundnuts (Snapp, 2014). As pigeon peas regrow in the second season, they can compete with more aggressive crops such as maize. Using this rotation, soil fertility is improved for the maize crop, while human nutrition is improved by including groundnuts and pigeon peas. Importantly, shrubby pigeon pea intercrops and rotations decrease fertilizer requirements (Figure 6), improve fertilizer-use efficiency, raise protein yields, increase carbon and nitrogen assimilation and phosphorus availability, provide greater soil cover and increase value–cost ratios (Snapp, 2014). Such ecological trade-offs are important. For example, by adding pennycress as ground cover within a maize–soybean rotation on cropped land in Minnesota (Figure 7), sediment loss to the Missouri River, and ultimately, the Gulf of Mexico, was greatly reduced (Runck et al., 2014). Selection of plants with desirable traits for such complex systems should further improve system performance and sustainability.

**Figure 6.** Shrubby pigeon pea intercrops (SP-intercrop) and shrubby pigeon pea rotations (SP-rotation) improve value–cost ratio (VCR), fertilizer efficiency, protein yields and provide greater cover compared with monoculture maize

Trees can also contribute positively to the complexity and stability of the landscape and the production system. *Faidherbia albida* is a leguminous fodder tree native to Africa that is dormant in the wet season, but active in the dry season. A maize crop as understory can be grown in the wet season with nitrogen benefits through leaf drop from the tree, after which the tree produces standing dry season fodder reserves for livestock (Dixon and Garrity, 2014). This system is compatible with other crops or mixtures being grown under the trees in the wet season, and with livestock supplements such as water, salt, and molasses-urea being
provided during the dry season. *Faidherbia* is native to sub-Saharan Africa, and is now being promoted and adopted widely in Africa and elsewhere because of its desirable attributes. Another example is the three-layered system with coconuts (tall), oil palm (intermediate) and annual crops (short). The resilient or drought-tolerant perennials shelter the more sensitive crops in the understory, a principle used to sustain agriculture in oases even in desert regions such as Morocco. As systems become more complex, they approach the perennial polyculture. The return to greater system complexity restores ecosystem services (Figure 8), analogous to the original system (Reganold, 2014).

Participatory agroforestry can break the land degradation–social deprivation cycle in shifting agriculture, using improved two-year legume fallows, participatory selection, and value adding of forest products (Leakey, 2014). These examples demonstrate the benefits of ecosystem complexity for sustained performance, while retaining biodiversity, assuring nutrient cycling, and improving farmer and consumer livelihoods and nutrition.
**Issues for selection in mixed systems**

In selecting for performance in mixed systems, the same principles that are used in monocrop systems still apply, and mixtures can over-yield relative to conventional monoculture. It is essential to evaluate the performance of the mixture in the conditions under which it is intended to be grown. So if the system is rainfed on soils of low fertility with material cut for hay or grazed early in the cycle or after harvest, then evaluation should be conducted under the same conditions. It is important to consider the performance of the system, rather than that of the individual components. In other words, in a dual-purpose perennial wheat crop with an undersown legume for grain and graze, the measure of success may be livestock performance rather than the grain yield of either crop. Furthermore, the characteristics for superior performance in mixtures may differ from those for a pure stand. Consequently, agroecological systems lend themselves to participatory selection *in situ*, so there is an opportunity for smallholders to favour their own preferences in selection. A prerequisite for this would be that smallholders have access to a wide variety of genetic variation, from which they can make selections. This seems to run against the prevailing paradigm on patenting and certification of seed as opposed to promoting seed saving by farmers.

The discussion presented above is founded upon the broader underpinning scientific principles (Allard, 1960), which also apply in participatory selection. It is important to understand the characteristics of the target population of environments (and their management regimes), and choose representative sites and conditions for evaluation of the diverse materials assembled, under conditions that are representative of how they will be used (Wade et al., 1996). Promising materials can then be further tested in individual villages or farms for local preferences. It is important to recognize constraints to selection progress, such as genotype by environment interaction, and to keep these constraints in mind while making selections (Wade et al., 1999).
For stability of performance, for example, the plants and mixtures may need to be selected for resilience under drought. In this case, it is essential to make selections when the relevant stress is encountered. If selections are made under all conditions and not just the target conditions, successive rounds of selection can result in a loss of genetic gains. There is a more complex model, involving selection for potential performance and performance under stress, but that requires a more formal programme to ensure materials with both desired attributes are retained. It may still be accomplished under participatory selection, but is likely to require larger populations, keeping of records, and selection based on performance in both seasons together rather than one after the other. Efforts to do this properly should bring rewards, but requires more work.

The above comments should apply when materials are already reasonably adapted, so further iterative gains can be made by participatory selection in situ. However, challenges could arise, requiring a more formal breeding programme or a larger research investment for success. For example, the advent of a serious disease such as a root or crown rot may require specialist attention, including molecular approaches. Likewise, for sustained progress in improved nutrition quality, it may be essential to measure micronutrient content or concentrations of chemicals which inhibit digestibility of forage. If abiotic stress tolerance was not present in the available materials, pre-breeding may be required to recruit suitable plants for evaluation in mixed systems, in order to secure plants possessing the essential suite of abiotic or biotic tolerances that can perform as required.

Species that are pre-adapted to grazing have evolved with their grazer. Plants developed adaptations to allow them to be grazed, e.g. protected growing points low in the canopy in grasses, while animals adapted mouthparts and digestive flora suited to dealing with various plant constituents, as well as the capacity to forage widely, become fertile and produce surviving young, even in harsh conditions. Thus, for mixed systems including livestock, the principles of co-evolution and joint selection also apply. It may be possible to select plants that are better performing in mixtures under grazing, and livestock better able to perform with the materials on offer. Co-evolution in natural systems can be used as a model for selection in managed systems.

**DISCUSSION**

In designing mixtures, it is possible to consider combining cultivars of a species as well as mixtures of different species. Cultivar mixtures have been advocated for stability of performance, especially under disease pressure, and in particular to reduce selection pressure on the pathogen so new sources of plant resistance are not required. In monoculture systems, variety mixtures or multilines are normally chosen for phenotypic consistency, so they flower and mature together for ease of harvest. However, when applying the new agroecological principles of polyculture, different traits may be required.

Under conditions of subsistence agriculture, where a range of flowering times could improve system stability, farmers can harvest materials as they mature. Again, the consequences of the mixtures on system performance should be considered. For example, a range of flowering times in a vigorous cereal or forage grass may compete more effectively with a legume component than a single phenotype.
In extreme cases, polyculture systems may have undesirable characteristics. Combined harvest of the mixture and sale as muesli may be appealing, but variability in content and feed value may make marketing more difficult. Usually markets require consistency in product with suitable labelling. Agroecological markets will need to be built that respond to and valorise the complexity of diverse farming systems.

Plants for a mixture could be chosen simply by trying lots of species or cultivars in combined plantings and evaluating them in the target environments, but additional benefits may accrue with a targeted strategy. By considering the characteristics of the target environment, the management system to be imposed and the desired products, species or cultivars may be selected for evaluation based on the required characteristics relative to system constraints. For example, if phosphorus is sparingly available on target soils, consideration should be given to including species in the mixture with enhanced capacity to mobilize phosphorus (e.g. legumes whose root systems release organic acids). If the soil is hard, choose one species with hardpan penetration ability. If leaching is a problem, choose a crop with extensive roots to mop-up nitrate and water from depth. For soil erosion, permanent ground cover is needed, so inclusion of perennial species is favoured. For root and crown rots, rotate brassicas such as mustard and canola for release of glucosinilates. For effective pollination of sensitive species, include plants with nectaries to encourage bees, and likewise, companion species for integrated pest management. Plants with mycorrhizal associations may further assist resource capture.

The appropriate manipulation of the mixture is important to enhance resource capture by encouraging the release and uptake of limiting elements, and including compatible plant types to ensure activity throughout the growing season, so resources are not lost to contaminate the environment. Likewise, the mixture should be tailored to ensure the delivery of products with desired nutritional and other qualities for humans and livestock as needed. In choosing plants for the mixture, performance in pure stands provides some reference indication of performance capacity, particularly in terms of phenotypic stability, disease resistance and nutritional value. By considering desirable traits needed in the target environment and management system, suitable plants can be included and evaluated for performance in mixtures in those situations, and the best system (not individual) performers can be identified.

While it is desirable to conduct local fine tuning for particular situations or farmer or consumer preferences, it should also be possible to identify broader requirements associated with target systems, regions or major soil groups, so materials passed for local evaluation are already known to be promising in the expected conditions. Participatory selection in the farm or village can then provide the best local outcomes as they are desired, including issues of cultural sensitivity, social justice and economic viability within the local system.

For participatory selection to be effective, sufficient diversity must be available to permit selection advance, under conditions that are consistent with the expression of the desirable traits. This process needs to be examined rigorously by monitoring progress in farmer selection, quantifying the genetic advance, and by tracking which genes are responsible and whether they are expressed universally or under particular conditions. Such knowledge should assist sustained genetic advance in participatory selection.
CONCLUSIONS

This chapter has outlined how genetic improvements could be secured in mixed farming systems, in which combinations of species are included for agroecological stability. The principles of crop improvement are used as a basis for identifying how progress can be made in mixtures. Selection should be strictly conducted under conditions representative of the target. Plants for evaluation can be considered according to how the traits they possess can be of advantage, and success must be measured for the system rather than the individual. There is a role for participatory selection to ensure local adaptations meet farmer and consumer preferences. At the same time, more complex challenges may require a more formal breeding programme, to ensure suitable plants for agroecological evaluation in mixtures are available. Ultimately, it is the in situ performance of mixtures that counts here.

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REFERENCES


