Ecological Cropping Systems – An Organic Target

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ABSTRACT

Organic agriculture has expanded rapidly but is now in danger of reaching a plateau of productivity and of contributions to ecosystems. There is an urgent need for major development of ecologically sound cropping systems using knowledge from ecological sciences and from appropriate breeding and selection. One of the most important aspects of successful natural ecosystems is their fine-grained plant diversity. Parallel examples in agricultural systems are considered including variety and species mixtures together with other intercropping approaches. These are integrated into potential organic cropping systems that eliminate the need for separate rotation phases for production and fertility building. At the highest organizational level, such approaches to diversity can be integrated into organic agroforestry systems. Stress is laid not only on the value of such diversified systems for sustaining their own productivity, but also on ways in which such systems can contribute to integration with other ecosystems and hence to increases in ecosystem services.

INTRODUCTION

Organic agriculture has expanded rapidly over the last thirty years. The area certified as organic or in conversion has increased greatly (though much of the converted area is permanent pasture) and sales have exploded (though an uncomfortably large proportion is from imported produce). Much of this change has been achieved through relatively simple modifications of currently conventional agriculture systems that help to reduce negative ecological impacts, although gross production per hectare over a whole rotation is significantly less. Organic agriculture does offer other positive ecological gains (biodiversity, energy use, decentralization, etc.) relative to conventional, but there is much still to be learnt from the positive ecological impacts and sustainability of natural (unmanaged) ecosystems. Indeed, application of advances in ecological sciences, both within the cropped area and by integrating agriculture with its surrounding ecosystems, is essential. Organic agriculture must become more ecologically oriented, not only as a way of farming, but to blend more with other ecosystems while simultaneously influencing outputs (marketing, food, energy, recycling). A fundamental starting-point in this direction is in the development of ecological cropping systems.

Current organic practice in terms of cropping systems has settled into a limited range of relatively short rotations based on monoculture cropping. For example, a recent survey (A. Lamy, S. Tehard, personal communication) recorded that the commonest cropping system is a monoculture rotation:

Winter cereals – pulses – spring cereals – two year ley

In which, most commonly, the cereals are wheat and the pulses are beans.

Variants on this theme include either more winter cereals and more ley, or, more cereals with a winter and two spring cereal crops, each cereal crop being separated by other crops including pulses. But if we continue only in this way, there is a danger of reaching a plateau of productivity with little scope either for increases in outputs or decreases in inputs.

This would also imply a plateau of contributions to and from ecosystem services (those processes and functions that occur naturally in healthy ecosystems and that benefit human society; Costanza *et al*., 1997). Examples of ecosystem services include carbon sequestration, nutrient cycling, pest and disease buffering, pollination and water cycling and purification. Integrating more of the principles and materials from natural into agricultural ecosystems should help to increase and sustain those services. Examples would be by increasing the activity of soil micro-organisms or providing safe habitat for a wide range of bee species.

MODELS FOR NEW DIRECTIONS: USING DIVERSITY

To develop an ecologically richer agriculture, we need a model to work towards which would be close to a successful natural ecosystem. Here, we are helped considerably by the work of David Tilman and his colleagues (Tilman, 1988). They have shown how grassland communities can be highly productive, season after season, with inputs limited to sun, soil, air and water. Their studies have revealed the increased productivity of the plant community compared with that of its components grown as sole stands. Some of the main mechanisms responsible for such improvements are:

a) increased range of functions as the number of community components increases
b) niche differentiation among the components improves exploitation of the local environment
c) complementation of functions among different components.

Such mechanisms need to be dynamic because of the changing nature of the environmental challenge. This is provided partly by frequency changes within the community to ensure the best available population structure for each set of circumstances. However, to ensure long-term adaptability, there is also the potential for genetic change within the community; new assemblages of characters are frequently available.

Other areas of ecological research are revealing many more mechanisms operating in the interactions among organisms than were previously known. Some examples are: emerging knowledge of mycorrhizal functions in soil, the positions of beneficial invertebrates in food webs, the structure and function of semiochemicals in plants and animals (Chamberlain *et al*., 2000), self-medication in animals (Engel, 2002) and even the use of noise by some insects to protect themselves against others. All of these developments, and others, represent potential new opportunities in ecological agriculture, particularly if they are considered not as individual ‘silver bullets’, but rather to provide and encourage synergistic interactions in a wide range of directions improving the overall robustness of the system.

MODELS FOR NEW DIRECTIONS: BREEDING FOR DIVERSITY

There are two genetical requirements that are fundamental to any major shift towards the use of diversity in cropping systems. The first is for crop genotypes that are able to thrive together (ecological combining ability). This may be achieved to some extent by selection among existing genotypes but is more likely to need appropriate selection within breeding programmes. The second is to maintain a level of genetic variability in the varieties used to provide in-built buffering against environmental variation, which is greater in organic /ecological agriculture relative to conventional.

One approach to both of these needs is DEFRA project AR0914. This project has developed a series of composite cross populations in wheat, the F1 generation of which has been planted at four different field sites to produce a series of F2 populations for harvest in 2004. The source of the composite cross bulk populations is a series of crosses made in all combinations among 20 wheat varieties selected on the basis of their large-scale, long-term success either as high-yielding or as high grain quality varieties. The bulks will be allowed largely to self-select under conventional, integrated or organic management for several years. This should provide unique insights into wheat evolution under different selection regimes and, simultaneously, valuable genetic resources adapted to those different regimes. From the organic selection regime, it is hoped to produce segregating population samples that are both adapted to organic production and that retain adaptability to the environmental variability that is inevitable under organic farming.

One important comparison will be between the population based on high quality varieties and the parents of that bulk grown as pure stands, to determine whether or not the bulk provides useful quality, for example, through complementation of characters from different parents. A second relates to the stability of quality: is the quality population more stable than the parents in terms of grain quality when grown across different environments?

If the populations provide useful material for cropping directly, there will also be questions concerning the larger scale production of the material. Can it be traded and under what basis? Can new rules be introduced or will it depend on the development, for example, of appropriate farmer clubs? Indeed, if we are to embrace fully the approaches that will improve both productivity and sustainability, we will need to be prepared for appropriate changes in the framework of administrative, legal and marketing structures.

BUILDING DIVERSITY IN PRACTICE

The underlying principle of the model approach described above is fine-grained diversity. In agricultural terms this means diversity of crop and non-crop plants to provide many different functions and outputs. This can be built up from the level of the gene in a simple scheme:

A. Crop diversity

Crop diversity can be considered at the level of the gene (e.g. lines or genotypes of a particular variety with different resistance genes), variety (within each species, different varieties cover a range of characteristics), or species.

B. Spatial arrangement

This refers to the ways in which the different forms of crop diversity, noted above, can be arranged in space. These are listed in order of decreasing variety/species interaction:

Mixed – (lines, varieties or species) planted in an ordered arrangement (Weiner *et al*., 2001) or at random
Row – alternating forms of diversity in row planting
Strip – alternating forms of diversity in strip planting

Plot or Crop area (from small plots to larger fields)

Monoculture in large fields is the arrangement most likely to encourage spread of pests and diseases. However, arranging even a small number of varieties in small rather than large blocks can have a large effect in delaying epidemic development (S. Phillips, personal communication). Reducing plot size to that of a single plant will maximize such effects.

C. Temporal arrangement

This refers to the ways in which the different forms of crop diversity, noted above, can be arranged in time. The principal forms are rotation, which ensures diversity between seasons, and sequential, involving diversity within a season. Rotation may be regarded as ‘unnatural’ but is particularly important for restriction of weeds, soil-borne pathogens and animal parasites. It helps to deal with the unwanted features of natural ecosystems such as major shifts in plant succession and loss of species.

It is important to stress that all forms of arrangement can be used simultaneously, for example, in our own organic agroforestry systems, where rotation of different crop species and varieties grown as mixtures is carried out in strips alternating with tree strips (mixed species), each of which has a mixed understorey of non-crop plants.

Examples of crop diversity arranged in random mixtures

A large body of experimental evidence (Finckh *et al*., 2000) confirms that random mixing of varieties can have a large effect in delaying development of foliar diseases in particular, though positive effects with soil-borne diseases were also demonstrated. The largest effects with foliar diseases are observed with plants that are individually small (such as cereals) and pathogens with relatively flat spore dispersal gradients (for example, mildews and rusts) (Garrett and Mundt, 1999).

Table 1. Organically grown mixture of three wheat varieties showing high yield stability over four years.

Variety	2000	2001	2002	2003	Means
Mixture	108	106	111	113	110
Hereward	106	111	84	120	104
Shamrock	91	111	106	98	101
Malacca	103	77	110	82	95
Pure variety means t/ha	4.07	2.53	3.99	3.47	3.51

A recent example of organically grown wheat mixtures is shown in Table 1. The commonest diseases over the trial period were powdery mildew, leaf rust and *Septoria tritici* although disease levels were generally not high. The mixture reduced the leaf cover of all diseases by about half. From Fig. 1, the yield of the mixture varied less from year to year than did that of the other components and, on average, was higher. In two years (2001, 2003), one of the components yielded more than the mixture but this was not predictable.

Precise reasons for the improved yield of the mixture are not known, though from previous work with fungicide-treated controls we can predict that an important part of the effect was due to reduced disease. Other data suggest that such variety mixtures might also restrict weed development. This could be due, at least in part, to reduced disease which would allow the crop plants to be more vigorous and thus better able to compete with weeds.

Although much of the earlier work on mixtures was completed on small plot trials, the positive benefits increase as the scale of mixture production increases. For example, large-scale (350,000 ha) use of mixtures of barley varieties in the former German Democratic Republic was highly successful (Finckh *et al*., 2000). Also, in China, large-scale trials with rice mixtures to reduce the effects of blast were taken up with great enthusiasm by local farmers (Zhu *et al*., 2000; Wolfe 2000).

Cereals have been the major target for mixture research, but similar effects have been observed for an increasingly wide range of annual and perennial crops. Recently, under organic conditions, we have found reductions in late blight in potato variety mixtures (S. Phillips, personal communication). This work highlights the importance of ecological combining ability among varieties in that some varieties performed better when mixed with some others. For example, there is positive synergism in mixtures of Cara and Sante because Cara performs better when not competing with itself and it also helps to protect Sante from blight, so improving the performance of the latter. Thus recommendations on growing mixtures need to be based on appropriate field trials, and breeding programmes could be designed to select varieties that are particularly suited to production in mixtures.

The question of selection applies also to mixtures of species which have shown considerable potential in terms, again, of yield stability and restriction of diseases, pests and weeds (e.g. Bulson *et al*., 1990). Many different combinations are possible, driven often by the potential use of the combined crop product, such as wheat and beans or barley and peas for feed, either as silage or grain. Interestingly, many successful examples involve species of cereal and legume which are complementary in terms of both agronomy and human diet.

Examples of other forms of spatial arrangement

An important ecological objective for intercropping is the notion of simultaneous cultivation of production crops with fertility-building crops, largely to avoid periods without a cash return from part of the cropping area (e.g. www.intercrop.dk). Our own preliminary work in intercropping is reported in two MAFF projects (OF 0173, OF 0181). The first was concerned with intercropping cereals and legumes and the second with vegetables and legumes. Some of the lessons from the two projects were:

a) White clover is not only an aggressive competitor but it allows little release of accumulated nitrogen while it remains alive.

b) Some crops are better-suited than others to legume intercropping. For example, among cereals, oats is well able to cope with clover competition whereas triticale is not. Among vegetables, root and leaf beet crops thrived whereas onions, leeks etc., did less well.

c) Any yield reductions in intercropping can be offset against later gains in the rotation due to the previous presence of clover and other crops (see below). The important point is that the clover crop occupies the inter-row spaces (about 60% of the field area) that would otherwise be bare or occupied by weeds, giving more efficient land use.

d) Pests and diseases occurred in the systems but only to minor levels. Slugs also occurred but were of little consequence. Weeds were severely restricted by the clover bands.

e) Specialized machinery is needed (see reports) for example for mowing the bands of clover grown between the crop bands. This is essential to delay ingress of grass weeds into the clover. The clover bands made the system easily workable.

Diversity in time: building a cropping system

For most field vegetables, a rotational break of 4-6 years is needed between crops of the same species. This often translates to a six year rotation overall in which two of the years are used for fertility building based on legumes or legume mixtures. Cash income is thus limited to two-thirds of the cropping cycle and fertility building to only one third.

With the vegetable-legume intercrop, fertility was not made directly available to the current vegetable crops. However, crop performance following three years of vegetable rotation intercropping was outstanding. The intercrop area was ploughed in during the early spring of 2003 and planted with potato trials. From these trials, mixtures of Cara and Sante averaged 32.1 t/ha in a dry season with no irrigation (Cara alone averaged 27.3 and Sante 31.1 t/ha). In other words, the fertility building role of the vegetable-clover intercrop was highly effective which means that any deficiency in vegetable production has to be discounted against more efficient land use during the rotation and high yields from the subsequent crop(s) (see point c. above). In a conventional organic production system, production of potatoes after three years of vegetables would not be an economic option.

From the experience with potatoes following vegetable-legumes, it seems likely that the potato crop benefited from the nitrogen and phosphorus made available from the legume crop and mycorrhizae but possibly also from potassium which may have been dissolved through citrate release from the beet crops (basic soil analysis Index values for P and K were around 1).

Similar results are being obtained from cereal – clover intercropping. Yields from winter wheat, oats, barley and triticale grown in a clover ley were less than those grown without clover, but the overwintering aftermath from the intercropping is a dense clover ley which will provide high fertility for subsequent spring cereals. An obvious advantage during the intercrop phase was strong suppression of weeds relative to plots with no intercrop despite mechanical weeding in the latter plots. Less obvious were other probable advantages of the cover crop including provision of habitat, reduction in leaching etc.

These results indicate the potential for development of improved cropping systems which could follow rotations such as:

Vegetable – legume intercrop (3 years, possibly more), potatoes (1 year), cereal – legume intercrop (2 years), then return to the vegetable - legume intercrop.

The vegetable part of the system would be based on a rotation among Alliums, Betae, Brassicas, Crucifers, Legumes and Umbellifers grown in the smallest convenient areas of each. The overall six year rotation would not require a separate fertility building phase, though a ley could be introduced as required if there was a need for livestock production. The cereal proportion in the rotation could be increased by reducing the vegetable cropping frequency. Alternatively, different parts of the farm could have a high vegetable or a high cereal frequency using the same basic system. Other options should evolve, varying, for example, the legume species (or mixture) and, perhaps more importantly, increasing the range of useful species incorporated at each stage of the rotation.

QUALITY AND MARKETING

A crucial question that follows any increase in the diversity and complexity of cropping systems is the impact of such systems on marketing. However, the ideal for any organic system is local and decentralized systems of marketing whether for individual consumers or other processors and users. Such systems depend on a wide range of produce. This can be achieved only through localized diversity of production which should help to ensure continuity because of maintenance of soil quality and protection from depredation by pests and diseases. These aspects can be improved further through development of local marketing co-operatives: one example is the recently formed Eostre Organics in East Anglia whose twelve organic growers supply directly markets, box schemes and school and hospital interests.

At the finer levels, mixing represents the greatest potential complication in terms of crop quality, particularly for cereal variety mixtures (large-scale mixed potato bulks can be separated into their components by Optical Character Recognition systems). However, it can be argued that variety mixtures may be beneficial for quality because a range of samples of a particular cereal mixture is likely to be more stable than a similar range of samples of any of the components. The major stipulation would be that the mixture components should be of similar quality or have desired compensatory qualities. The outstanding example of spring malting barley mixtures in the former GDR shows what can be achieved in this way; high quality malt was produced and a large proportion exported successfully to western Europe.

ORGANIC AGROFORESTRY: THE ULTIMATE SYSTEM?

The discussion so far has centred on incorporation of diversity into systems of cropping annual species. Agroforestry opens up the potential for integrating perennial species into cropping systems. There are many possible advantages including more effective nutrient cycling, carbon sequestration, shelter for crops, animals and humans, greater opportunities for pest and disease control, a wider range of products on the farm, better spread of labour use through the year, a large increase in biodiversity and extended aesthetic interest.

Although many different forms of integration of crops and trees are possible, the most common is some form of alley cropping in which a suitably sized crop alley is sited between lines or bands of trees running in a north-south direction. Such systems of 'production hedges' update the older northern European agroforestry system of hedgerows (Gordon and Newman, 1997). Organic (ecological) agroforestry systems should be highly diversified to maximise the generation of ecosystem services from farmland.

Organic agroforestry systems being tried at Wakelyns Agroforestry, include mixed hardwood standards (Ash, Hornbeam, Italian Alder, Oak, Small-leaved Lime, Sycamore, Wild Cherry) planted in randomized sets. One variant includes dispersed apple trees to reduce the rate of spread of apple pests and pathogens. Other examples are based on mixed fruit species with fruit and nut shrub understorey, or walnut and plum with clover understorey. There are also two hardwood coppice systems, one based on a hazel population and a second on a willow variety mixture. Alternate willow hedges are coppiced each year. Cut willow is air-dried in the field for one year, delivering the estimated equivalent of more than 12 t/ha dry wood per annum. Some stems are sold for craft use, but most are now used for heating.

From observation, it is difficult to say precisely which gains are being achieved and to what extent. Carbon sequestration is clear with little obvious impact on crop production. Reductions are limited to about one metre from the tree line, and are species dependent, for example, wheat appears more sensitive than oats to tree competition. Also, coppiced willow appears more sensitive to crop competition than do non-coppiced species. In terms of nutrient cycling, as the trees develop, there is an increasing spread of leaf litter across the cropping alleys. Complete food webs have established in the tree strips evidenced by vole and barn owl activity. The range of bird species is considerable and probably increasing (R. Fuller, personal communication). This means that the tree strips are acting as 'beetle banks', providing habitat for beneficial invertebrates. The agroforestry areas have become aesthetically interesting, sufficiently so as to attract the eye of some local artists.

In collaboration with Sheepdrove Organic Farm, a tree alley system on that farm has been integrated with poultry production (silvo-poultry system). The tree strips in this case include a range of standards, hedge plants and shrubs selected partly for shelter and partly for diversity of food. In addition, there is a complex herbage understorey to provide a range of plants with potential medicinal value including anti-bacterial, anthelminthic, expectorant, calming and other qualities. This herbage system was devised by Cindy Engel (see Engel, 2002).

CONCLUSIONS

Recently, there have been numerous and diverse developments in ecological sciences that are improving our understanding of both natural and agro-ecosystems. There is now a need for greater application of established and emerging ecological principles into agricultural systems, most obviously through improvements in cropping systems.

Examples given include increases in spatial and temporal diversity at the levels of genes, varieties and species, up to the development of fully integrated agroforestry systems. Future developments will include more precise use of such diversity based on, for example, further discoveries in chemical, physical and biological signalling systems and in other interactions among plants and animals. Integrating such examples into cropping systems can provide new approaches to organic farming that improve and stabilise productivity while increasing the ecological benefits of the farming system. Such applications of ecology are essential, partly because of their importance in replacing synthetic inputs in agriculture, partly to improve the contribution of agriculture to ecosystem services, and partly to provide better integration of natural and agro-ecosystems because of their inter-dependence.

These ecological and agricultural elements need to be brought together in a modern form of certified organic agriculture. This should produce a multi-faceted output well beyond improvements in biodiversity and yield, including a balanced and diverse output for ideal dietary needs, energy savings, energy generation, wildlife, support and development of rural society, more aesthetically appealing countryside and greater opportunities for education and leisure in the natural and farmed environment (see also Tudge, 2003).

Such changes will pay for themselves in the long-term, but in the short term there is a need for greater investment into appropriate ecological and cropping research. This is consistent with current Government policy on sustainability, biodiversity and renewable energy. But policy development needs to go much further in this direction not only in the UK but also in relation to reform of the Common Agricultural Policy.

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