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SUSTAINABLE AGRICULTURE: MORE THAN ONE WAY AHEAD

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Summary. Recent discussions of the way ahead for agriculture have tended to centre around the frequently incompatible claims of the proponents of technological agriculture, now further developed through inputs from biotechnology, and ecological agriculture, of which organic farming is the best known example.There is a need for the claims made for these two versions to be put into a broader scientific and social context and to ask whether they might both represent different sustainable options for the future.

Conventional and ecological agriculture are based upon distinct but different paradigms. Conventional agriculture has many similarities to other industries. Its management is dominated by a series of simple linear models e.g. weed plus herbicide equals solution and the aim of externalising many costs. In contrast ecological agriculture is based upon linked networks and an explicit view of objectives being achieved through the summation of a series of partial solutions. Such systems aim to internalise many of the costs of other systems. Such differences in philosophy require their driving areas of science to be compared so as to identify the contributions that they might make to sustainable objectives and to identify the extent to which they might be able to co-exist in the future.

Ecological (organic) agriculture is centred around both the holistic system; a range of crops/animals are produced on a farm at the same time, and the rotation; the various farm activities occurring in sequence on a single field. In such approaches, all activities influence all others and result in there being no need for inputs such as chemical fertilisers or pesticides to enter the system. Key science needs are thus the understanding of ecological linkages, especially in respect of nutrient transfers and pest/disease control and an understanding of the autecology of key organisms, both crop and soil micro organisms. Studies of the development and ultimate fate of crop roots and root systems and the role of arbuscular mycorrhizal (AM) fungi in the provision of crop nutrients and the maintenance of crop health have a critical role in relation to these objectives. Although, crop properties are important to agriculture DNA technologies, which are claimed to enhance crop properties, have been rejected by the organic sector. The basis of this rejection lies with both the linear thinking which underpin them and because they are seen as unhelpful in respect of the key underlying issues which organic agriculture seeks to deliver, e.g. reducing CO_2 release from non-renewable resources and increasing carbon sequestration.

In contrast biotechnological agriculture aims to use the contribution of genetics to the phenotypic response to agricultural problems e.g. avoidance of growth reduction due to a specific pathogen, as a means of permitting a wider range of crop species and varieties to give higher yields under a wider range of conditions. Gene transfer, using transgenic methodologies has the ability to make specific crops more resistant to pests and able to grow under conditions that are currently inhospitable e.g. high salt situations. These technologies have the ability to increase production and so world food supply although this may be as a result of continuing with long-term non-sustainable actions such as the use of non-renewable resources. The very different merits of biotech agriculture and ecological agriculture mean that they present very different visions of sustainability. How, together, on a world scale they might contribute to issues such as climate change and sustainable land use is the most important current question.

Introduction

A series of population and resource related questions have reopened the discussion about the sustainability of various systems of agriculture. This has prompted an evaluation of how these various systems might deliver against a series of generally agreed key goals. These are usually described as

a) the pressures of a rapidly increasing world population;
b) the amelioration of, and adaptation to, the effects of global climate change;
c) reducing the pressures of agricultural land-use on the natural environment and biological diversity;
d) improving human health through an appropriate diet.

That sustainable systems of agriculture must deliver on those objectives is generally acknowledged, but which system of agriculture provides the best fit with the above objectives is not agreed. At the current time strong claims are being made for both biotechnologically enhanced systems (systems based around GM crops) and ecological agriculture (e.g. organic farming). At a time when key decisions are likely to be made in the EU and WTO, there is a need to evaluate some of the claims made in respect of both approaches..

In this paper we identify and contrast what are often perceived as the two principal paradigms underpinning current agriculture. We also examine the research needs and scope for further development of the above approaches and relate these to what are commonly identified as the key issues which define sustainability in this context. Inherent in the title and subject of this paper is the issue of coexistence and so we attempt to identify some of the key issues associated with a joint approach to sustainability.

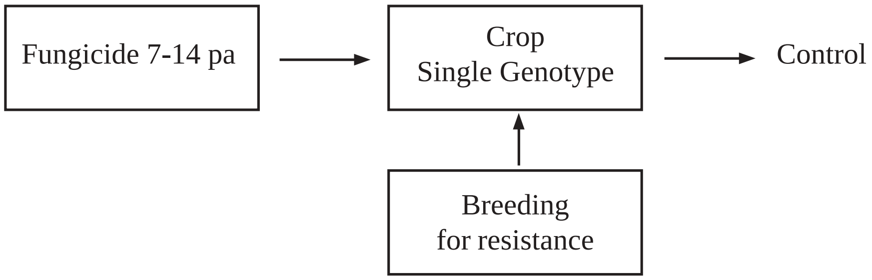
Agricultural Systems

Conventional and ecological agriculture are based upon distinct but very different paradigms. These are illustrated in Table 1 (Atkinson and Watson, 2000). Conventional agriculture has many similarities to other production industries. GM is the latest of a series of “new approaches”; synthetic fertiliser use became a significant element in the 1940s and pesticide use a significant element in the 1960s. Simple management is important and many operations are based on linear models. This is exemplified (Figure 1) by the approach to disease control. For the conventional system the ability to resist the impact of a disease depends upon the resistance conferred by plant breeding, which may in the future be enhanced by the insertion of genes using a transformation process, and the use of fungicides. For Phytophthora diseases this may require as many as 14 separate applications per season (Taylor et al, 2000). The key drivers of this type of system are high yields and low costs. In the drive to reduce the costs to the producer many costs are externalised, e.g. the costs of removing leached pesticide or nitrate residues from water or the costs of reducing the traditional size of the labour force (Pretty et al, 2000). Systems of this type can easily accept any new technologies which are consistent with simple management, e.g. making crops resistant to broad spectrum herbicides and increasing yields through improved weed control as with Roundup Ready and Liberty Link GM varieties..

For sytems of this type, where public funds are available to provide funding for environmental goods or where there are other reasons for developing alternative approaches eg. high chemical costs or conservation areas, then integrated crop management techniques may be used as a means of reducing environmental impact.

Farrell and Hart (1998) have detailed two contrasting concepts of sustainability. The “critical limits” version focuses on issues such as maximum populations, limitations to resource use and the need to maintain assett balances. This version of sustainability, which is at its heart mechanical, and human centred, links to, and sets criteria to judge the sustainability of conventional agriculture. In contrast, the ‘competing objectives’ view of sustainability aims to balance social, economic and ecological goals to meet both human needs and those of a healthy environment. This version

(a) Conventional



(b) Organic

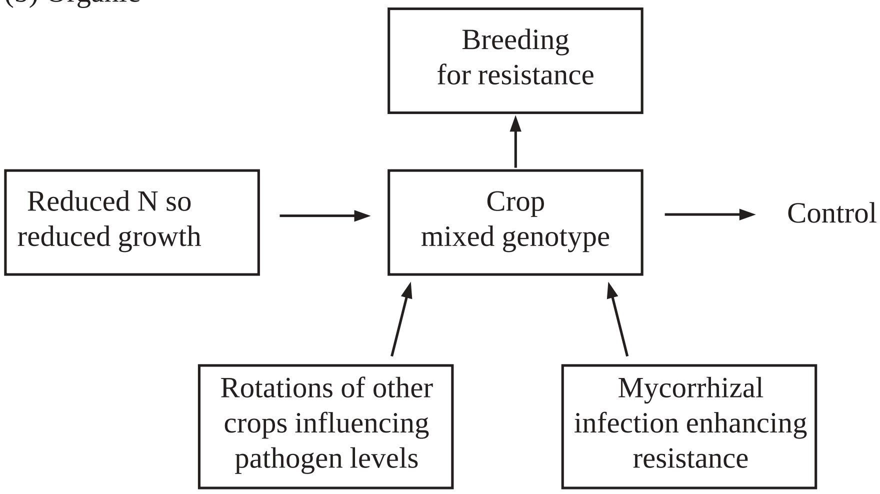


Figure 1. A comparison of the control of fungal pathogens (eg. *Phtophthora* sp) in (a) conventional and (b) organic production systems

sets criteria which can be used for organic agriculture. The criteria inherent in these two veins of sustainability indicate that the two systems will be easiest to compare at a high level and essentially on the basis of their ability to deliver the indicators of their version of sustainability. These issues are further discussed by Tait (2000).

In contrast to conventional agriculture ecological agriculture is based upon a series of linked networks. An early example of this is described by Summerhayes and Elton (1923) and the summation of a series of partial solutions (Figure 1). In contrast to the simplicity of the chemical control of plant diseases detailed for the conventional system an organic system depends upon the inherent resistance of a mix of different genotypes which thus reduce plant to plant spread of the disease, the enhanced resistance given by a significant level of arbuscular mycorrhyzal (AM) infection and the effect of the crop rotation on soil chemical and microbiological properties (Atkinson and Watson, 2000). An organic system is thus not one which avoids the use of chemicals but one which, when fully functional, does not need external inputs. The small range of chemical inputs allowed within organic systems recognises however that there are occasions when the normal biological control system fails and when, consequentially, some additional means of control will be needed. Organic systems by their design internalise many of the costs which are externalised by conventional systems. The effective management of organic systems require that nutrients are recycled and so systems design aims to prevent losses of nitrate through leaching and dentrification (Table 1).

As the inherent ability of a crop to resist disease is important to an organic system it might be thought that GM technologies aimed at enhancing resistance would be appropriate to such systems. The organic movement has however rejected GM technologies. The basis of this rejection is:

a) GM technologies allow specific remedies to be targeted on specific problems. This does not sit easily with the holistic approach of the organic movement (Table 1).

b) Most current GM cultivars are aimed at improving the effectiveness of crop protection, ie, reduced weed populations. These approaches are commonly inconsistent with the wider ecological objectives of organic systems.

c) Whilst the gene products used in transformations are normally well characterised, the position of their insertion into the genome is more random. Organic producers are concerned that this may change critical crop properties linked to food quality.

d) A number of projected GM cultivars are aimed at the cropping of land not currently suitable for arable agriculture or which has been damaged, eg. through salinity or by previous production practices, eg. ill-advised irrigation schemes. Organic farmers are concerned that GM technologies might encourage the maintenance of unsustainable or inadvisable practices, especially those which adversely influence and appropriate balance between agricultural and non-agricultural land use. These issues have been discussed further by Atkinson *et al* (2002).

The way ahead

The development of conventional agriculture is likely to be through a further increase in intensification and crop productivity. This will come through an extension of current practices and by the continued development of new pesticidal chemicals and by crop modifications using GM and conventional breeding technologies, to increase partitioning into harvestable components, to protect against pests and diseases and to permit crop production on land and soil types not currently suitable for arable production. Achieving these objectives will benefit from an improved understanding of both crop and soil biology., This is a shared aim with ecological agricultural systems. The opportunities for this, which will also influence the coexistence of GM and organic produc-

Table 1. The contrasting features of GM and Organic Agriculture

Key features of agriculture	System	
	Biotechnological(GM crops)	Ecological(organic)
Components	· Can be devoted entirely to crop production.	· Most commonly a mix of crops and animals. Rotations critical.
	· Nutrient supply based on fertilizers with application rates optimized for yields	· Nutrient supply resulting from rotational design. Additives from outwith system to enhance soil status
	· Crop protection dependent upon chemicals.	· Crop protection usually dependent upon natural biological processes.
	· GM varieties seen as a means of aiding chemical use, simplifying management and enhancing productivity.	· Consider GM varieties unnecessary, even inherently wrong, and dangerous to food quality and biodiversity.
Design aims	· Production of maximum economic yields.	· Production of good yields but ‘quality’ of higher priority
	· Cost minimization a key element, especially for crops traded in international markets	· Costs controlled but only to the extent which social and ecological objectives permit.
	· Environmental impact to meet legislative compliance. Some, eg LEAF farms, go much further and may aim to externalise costs	· Sympathy with the environment and biodiversity key aims
	· Impacts significant non-renewable resources, eg fertilizers, pesticides etc.	· Impacts used only in the event of systems failure so use restricted by system rules.
Sustainability concept	· Aligns to a ‘critical limits’ view.	· More comfortable with ‘competing objective’ view.

tion are now discussed in the context of studies of organic systems and especially in relation to the key need of reducing nutrient and disease related stresses.

Ecological Agriculture

Ecological agriculture is based on a holistic view of the agricultural system with, usually, crop and animal production being undertaken in a linked manner. For the purists the importance of holism means that they reject potential contributions of reductionist science on the basis that the total system is so much more than the sum of individual components and that the interactions between these components are more important than the individual components. This view emphasises the need for assessments to be made at a high level. Examples of this approach and of systems level nutrient balances are given by Atkinson and Watson (1996). Assessment made only at the systems level while aiding comparisons do not provide an easy means to develop the system. Developing a system in a logical manner is done most easily by detailed assessments of identified key elements and their interactions. The approach we have followed to experimentation on organic agriculture has been through a study of the cycling of nutrients at a systems level, through attempts to quantify the contributions of the rotation and by detailed studies of the dynamics of crop root systems and their mycorrhizal associates. Examples of such studies are detailed here as a means of illustrating the types of science which can underpin organic agriculture and of current developments in the autoecology of crop species relevant to organic systems but which may have a wider value.

A typical organic rotation is illustrated in Figure 2. The complete rotation results in a net increase in the nitrogen content of the soil which is an important component in the crop protection strategy illustrated in Figure 1. The various components of the rotation, the mycorrhizal status of the crops within the rotation and the development of a soil microflora which aid the suppression of some soil borne pathogenic fungi are all important deliverables of the rotation. The centrality of the soil component of the rotation, in respect of both nutrient cycles and plant health, suggests the critical importance of understanding the processes which deliver plant nutrients and health.

The contribution of crop roots

Crop root systems contain a significant proportion of the total carbon fixed by a crop. The proportion varies greatly between individual crop species. On the basis that a significant proportion of crop leaves survive for much of the season it has been assumed that most crop roots will be similarly long-lived. The development of mini rhizotron technologies, which allow roots to be viewed *in situ* in the soil has allowed root

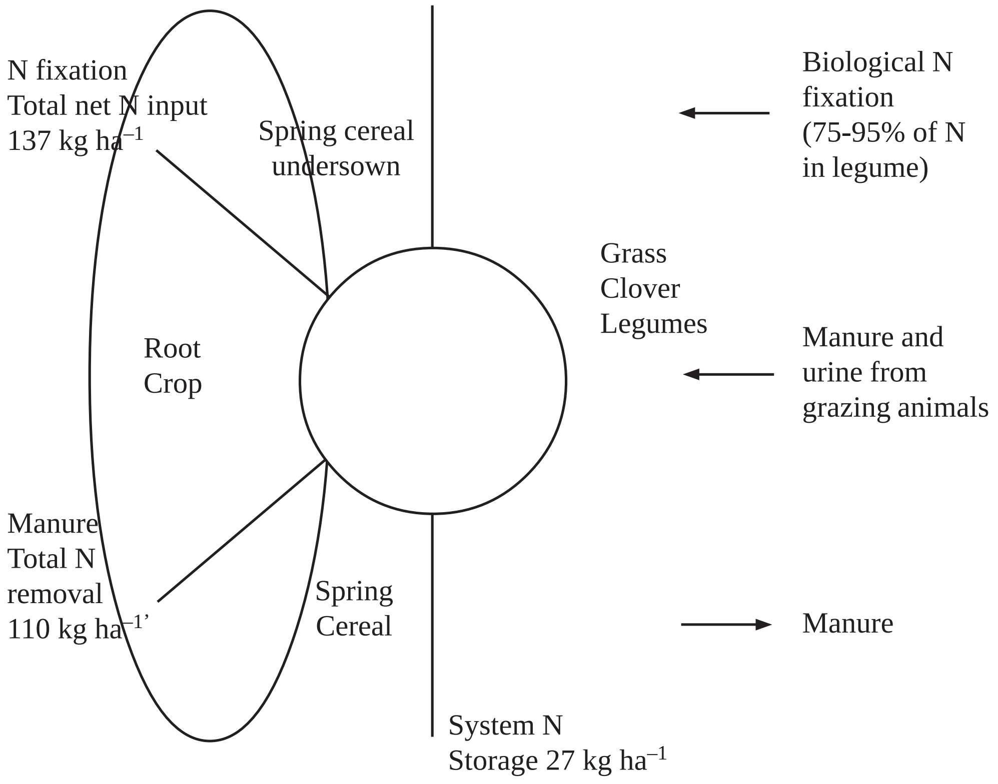


Figure 2. Nutrient cycling in an organic rotation

longevity to be assessed for a range of crops and for agricultural systems. Atkinson and Watson (2000b) compared the survival of the roots of five crop species. The results of this study are summarised in Table 2.

The longevity of the roots of the different crop species varied greatly. Seven days after root initiation, around 80% of the roots of white clover remained but only around 40% of those of oats or pea. After 6 weeks around 60% of white clover roots remained

Table 2. The relative survival of the roots of five crop species

Species	% Surviving after a given time (d)		
	7	**14**	**35**
Oats	43	40	10
Pea	43	40	12
Mustard	62	42	16
Red Clover	71	52	30
White Clover	78	73	54

but only around 10% of the roots of oats, pea or mustard. The roots of red clover survived for a significantly shorter time than was the case for the roots of white clover. In addition to the effects of crop species, root longevity has been shown to be greatly influenced by soil temperature (Watson *et al*, 2000) and by infection with AM fungi (Hooker *et al*, 1995). Studies of a range of crop and pasture species have thus indicated that substantial proportions of the total number of roots turnover within periods of days, rather than months. The reason for this short longevity is unknown but seems most likely to be related to the high carbon costs of root maintenance, the depletion of soil nutrients close to the root or the avoidance of soil borne diseases. This rapid turnover has however important implications for the movement of carbon from the atmosphere to soil carbon and for the recycling of nutrients within the soil. Black (1997) estimated the quantities of nitrogen which could be recycled through the absorption and subsequent release of nitrogen as a consequence of short periods of root longevity and rapid root decomposition. Estimates were based on a combination of measurements of the root standing crop, estimated by soil coring, mini rhizotron estimates of root turnover and measurements of root nitrogen content. It was assumed that nutrients were not re-translocated from a root prior to its death and that the field growing season was 20 weeks in length. On this basis the roots of *T. repens* turned over 221 $kg.ha^{-1}$ N if micorrhizal and 349 $kg.ha^{-1}$ if non-mycorrhizaL. Infection with AM fungi increased the percentage of roots living 6 weeks or longer from 20% to 37%. The impact of AM infection on root turnover varies between crop species. Nutrient storage and release from crop roots is an important component in system nutrient balances.

For most agricultural systems the role of the root system in nutrient and carbon cycles has been poorly explored. In woody perennials where, because of their complexity, there is most scope for variation in root systems to be expressed Lavender (1992) identified that some components of the root system were under strong genetic control, while others were highly vairable and a function of the environment in which the plant had been grown. In a series of experiments in which different clones of *Betula pendula* were grown with different levels of water, nitrogen or phosphorus, some characteristics remained relatively fixed and so clearly were genetically determined. Other characters varied substantially with variation in particular features of the growing environment ie. they were more environmentally determined. The mass (weight) of new, fine and woody roots, the mass per unit length of fine roots and the proportion of total assimilate allocated to woody root tissue all appeared to be genetically determined. These features could therefore be the subject of selection in a plant breeding programme. Other features such as the total size of the root system, both absolutely and relative to the above ground component and the mass per unit length of woody roots were environmentally determined and so represent the basis of the plants plastic response to a varying soil environment.

The ability of plant root systems to cope with environmental stresses, such as water stress, is a key feature of the ability of a crop plant to cope with sub-optimal conditions. The extent of repeatable variation within an individual species in relation to its ability to cope with water stress is poorly understood. It is however crucial to the development of programmes which aim to develop stress resistance through breeding. Information on this topic is also important to being able to identify the need for biotechnological methods to develop these properties in cultivars designed for sub-optimal conditions. Dassanayake (1996) assessed the impact of water stress, in the surface soil layers, on changes in the length the roots of three Fushcia varieties with different growth habits. Some information from this study is summarised in Table 3. All of the varieties modified their patterns of root growth in response to water stress. In all cultivars root length decreased in the droughted zone. The size of the reduction in root length was relatively similar for both secondary and tertiary roots. The resistance to drought of the roots at depth 2 varied between cultivars. Cultivar 2 showed little change relative to an untreated control. In cultivars 1 and 3 there was a nil or small negative effect on the secondary roots and an increase in the length of tertiary roots. In all cultivars root length, secondary and tertiary, increased at depth 3. The increase in cultivar 2 was large. These studies would suggest the existence of substantial variation in natural plastic response of plant roots in response to water stress. This variation can be used in the development of cultivars adapted to both stressful environments and organic systems. Analysis of the contribution of such variation to stress avoidance could usefully inform genetic transformation programmes.

Table 3. The effect of water stress in the soil surface (depth) on the changes in the lengths (% of unstressed control) of secondary (branches from primary roots) and tertiary (branches on secondary roots) roots of three varieties of Fushcia. Data from Dassanayake, 1996.

Depth	Root type	Variety		
		1	2	3
1	Secondary	–20	–38	–47
	Tertiary	–25	–41	–43
2	Secondary	0	–6	–11
	Tertiary	49	1	52
3	Secondary	69	537	72
	Tertiary	95	387	80

Mycorrhyzas and stress

Over recent years a series of studies by a range of authors have assessed the impact of AM fungi on the supply of water to the plant. The results of these studies have commonly been inconclusive. In contrast to studies of the ability of AM fungi to increase water supply Dunsiger (1999) investigated how poplar trees infected with one of a number of AM species were able to cope with stressful growing conditions. The performance of young AM infected trees were compared with uninfected controls. She found that, in AM infected plants, water use increased more rapidly with increasing leaf area than was the case for control, uninfected, plants. In addition, in plants infected with AM fungi 70% of leaves showed high rates of stomatal conductivity, 0.20–0.24 mol.m^{-2}.s^{-1}. Comparable values for non-infected plants were around 45%. In contrast some AM infected plants had leaves showing very low stomatal conductivity (0–0.004 mol.m^{-2}.s^{-1}). No control plants had conductivities this low. Despite this enhanced water use the under conditions of good water supply, under conditions of developing stress, water use was reduced more rapidly than in (control) uninfected plants (Figure 3). In both control and AM infected plants water use fell with decreasing soil water potential but the rate of decrease was higher for AM infected plants. AM fungi, which have long been known to influence nutrient uptake by plants and which have more recently been identified as conferring some resistance to pathogenic fungi, now appear to have a role in the adaptation of plants to water stress. The AM fungal relationship with plants is of ancient lineage. Consequently it would be natural to regard AM infection in plants as the normal state and thus uninfected plants as abnormal. On this basis it is perhaps not unusual that plants which lack their normal symbiosis are less well equipped to absorb nutrients, to regulate their water balance and to respond appropriately to pathogens. Further understanding of this important symbiosis will aid crop production in

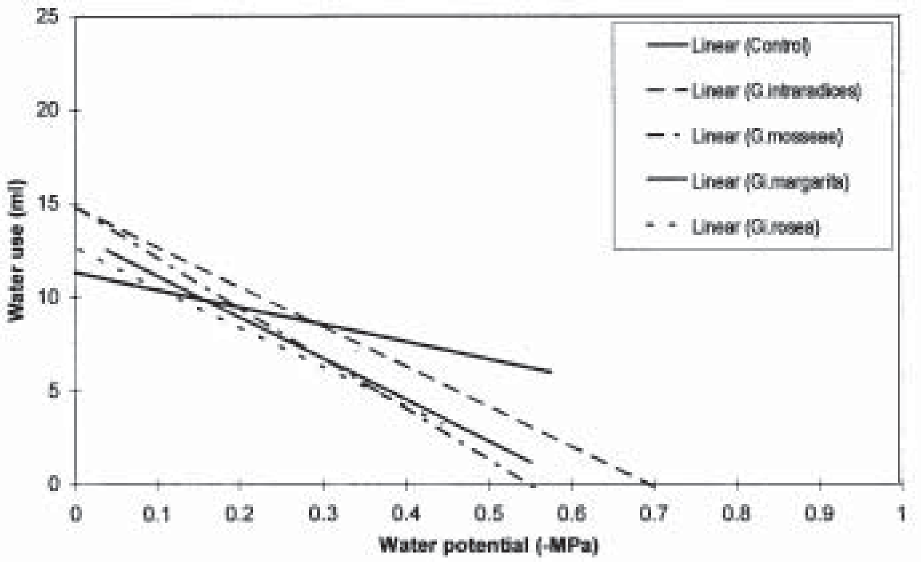


Figure 3. The effect of inoculation with AM fungi on the response of one month tree water use (ml) with decreasing soil water potential (-MPa). Data from Dunsiger (1999).

organic systems. The use of high levels of soluble nutrient (fertilisers) and fungicides in conventional agriculture impairs the development and functioning of AM fungi and the symbiosis. Some of the aims of GM technologies may simply be aimed at replacing the properties given by AM fungi but which are lost as a consequence of the use of fungicides.

Agricultural Systems and future challenges

Both conventional and ecological agricultural systems produce food, influence health, are critical to good environmental management and may be components within a wider solution to some of the problems related to global change. Potential contributions of the two systems are summarised in Table 4. Both systems can make positive contributions to the above issues but in different ways. The principle contribution of conventional/GM agriculture will be to volume of food production, especially in the West, while organic agriculture contributes substantially to other issues. It may also be the solution of choice where simplicity of management and cost reduction are not critical to production.

Conclusion

World food supply over the past 50 years has been the product of a series of systems and approaches. There is every reason to believe that this will continue. The advent of GM technologies raises the feasibility of a wider range of genes migrating to more non-target species than has previously been the case. This is a significant concern for the organic farming movement. Isolation of different production systems from genetic transfer is likely to be a key element in any plan for the coexistence of GM cropping systems and organic systems. The minimal R & D investment in organic systems over recent years suggests that there is substantial scope for these systems to increase their contribution to food production, health, environmental quality and global change amelioration. Detailed results presented here on the variation inherent in crop root systems and on the role of AM fungi in enhancing resistance to pathogenic and abiotic stresses, eg. water stress suggests that the potential for increasing the role of ecological agricultural systems is both substantial and real. On this basis, to argue that only GM technologies can meet agriculture’s key needs in the future, such as feeding an expanding world population, is myopic. In their own terms both GM and organic agriculture have ways in which they are sustainable. The key future issue is the value which society will place on different elements of sustainability.

Table 4. Potential contributions of conventional agriculture (including GM crops) and ecological agriculture to the amelioration of key issues in agriculture

Key issue	Conventional agriculture impact	Ecological agriculture impact
Food production amount	· Substantial record of increased production in western world	· Yield less than conventional. · R&D investment low.
	· GM technology may aid production on poorer soils	· Successful in late developing areas due to sociological fit
		· Limits untested.
Good quality and health	· Basic quality and freedom from disease biproducts good.	· Pest and plant disease damage can be an issue.
	· Concern over pesticide residues, antibiotic markers in GM foods and sensory attributes.	· Slower growing conditions and varieties used can aid sensory attributes.
		· Claims made for positive link to health.
Environmental impact	· Acknowledged to have adversely influenced biodiversity and non-GM species.	· Minimizes some of the adverse impact of agriculture on the environment.
	· Responsible for nutrients and crop protection materials entering water.	· Environmental management a key design feature of system.
	· Significant user of non-renewable resources.	· Minimises losses from the system.
		· Minimises use of non-renewable energies.
Global Climate change	· Directly and indirectly responsible for producing greenhouse gases.	· Proven record of improving soils and sequestering significant amounts of C.
	· GM technologies may enhance minimum cultivation and so increase C sequestration.	· Practices can be positive for reduced production of greenhouse gases.

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