Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems

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Eco-efficiency is concerned with the efficient and sustainable use of resources in farm production and land management. It can be increased either by altering the management of individual crop and livestock enterprises or by altering the land-use system. This paper concentrates on the effects of crop sequence and rotation on soil fertility and nutrient use efficiency. The potential importance of mixed farming involving both crops and livestock is stressed, particularly when the systems incorporate biological nitrogen fixation and manure recycling. There is, however, little evidence that the trend in developed countries to farm-level specialization is being reduced. In some circumstances legislation to restrict diffuse pollution may provide incentives for more diverse eco-efficient farming and in other circumstances price premia for produce from eco-efficient systems, such as organic farming, and subsidies for the provision of environmental services may provide economic incentives for the adoption of such systems. However, change is likely to be most rapid where the present systems lead to obvious reductions in the productive potential of the land, such as in areas experiencing salinization. In other situations, there is promise that eco-efficiency could be increased on an area-wide basis by the establishment of linkages between farms of contrasting type, particularly between specialist crop and livestock farms, with contracts for the transfer of manures and, to a lesser extent, feeds.

Keywords: integrated land management; sustainability; mixed farming; manures; rotations; nutrient management

1. INTRODUCTION

The concept of eco-efficiency has been developed in the last decade and has often been considered a key element in the development of sustainable farming systems. This paper considers the meaning of the term eco-efficiency before discussing the characteristics required for high eco-efficiency, concentrating on those relevant at the level of the farm and region. Examples are given from both temperate and tropical agriculture. Reasons for the low adoption of eco-efficient systems are discussed and approaches for increasing adoption rate are suggested.

(a) *What is eco-efficiency?*

Eco-efficiency was debated by the British Crop Protection Council (BCPC) Forum (2004) and by Atkinson & Wilkins (2004), but there is no single accepted definition of eco-efficiency. These two papers indicated that eco-efficiency is related to both 'ecology' and 'economy' and is concerned with the efficient and sustainable use of resources in farm production and land management. It was argued that there are not absolute standards which a system needs to satisfy in order to be classed as being eco-efficient, but eco-efficiency will be increased when a given level of production is achieved using less resources, with less losses to the environment and without sacrifice to

the productive potential of the land or economic performance. The efficient use of plant nutrients, pesticides and energy and the minimization of greenhouse gas emissions are all key concerns that affect eco-efficiency.

While eco-efficiency may be considered at the level of the crop or animal enterprise, it is more appropriate to consider eco-efficiency at a larger scale. The product mix on the farm will affect the efficiency of resource use and interactions between crop and livestock enterprises discussed later in this paper indicate the need for consideration at least at the level of the farm. The concept could be extended to include the whole food chain, with consideration not only of the life cycle of inputs to the farm, but also the transport and processing of the products from the farm. This introduces additional elements to the concept of eco-efficiency at the national and regional levels and may modify conclusions reached by consideration only at the level of the farm. For example, organic systems normally have high eco-efficiency at the farm level, but if the products are airfreighted across the world to the consumer, the overall food supply system will have low eco-efficiency. However, for simplicity, this paper will concentrate on eco-efficiency to the point of sale of products from the farming sector.

The BCPC Forum (2004) concluded that eco-efficient farming should satisfy the following five key attributes: (i) it uses resources efficiently and makes the maximum use of renewable inputs, (ii) it is neither locally polluting nor does it transfer pollution to

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elsewhere, (iii) it provides a predictable output, (iv) it conserves functional biodiversity in relation to strengthening ecological processes, reducing greenhouse gas emission and pollution generally and limiting soil erosion, and (v) it is capable of responding rapidly to changes in the social, economic and physical environment. It is also crucial that eco-efficient farming satisfies economic criteria in relation to farm profitability.

(b) Why increased concern for eco-efficiency?

During the mid-twentieth century, agricultural production throughout the world was directed towards increasing food production in order to satisfy both local and export demands. There was an agricultural revolution, particularly in developed countries, with large increases in production associated with improved varieties of crops, improved animal breeds and large inputs of fertilizers and crop and animal protection products. The increases in yield led to improved efficiency in the use of the natural resources of land, water and solar radiation. In an analysis of maize production in USA from 1945 to 1985, Evans (1996) found a straight-line relationship between energy input and energy output with a slope of approximately 3. He suggested that the absence of diminishing returns arose from (i) continuing succession of innovations, (ii) progressive improvement in the efficiency of input manufacture, formulation and use, and (iii) synergistic interactions between inputs. However, intensification of production has increased loss of potential pollutants to the atmosphere, particularly ammonia and the greenhouse gases nitrous oxide and methane, and to water, particularly nitrate and phosphate. Moreover, in large areas of the world, future production potential was compromised by soil erosion and soil salinization.

Associated with these developments were increased affluence and concerns for environmental protection and enhancement in developed economies and transition from food deficits to food surpluses, particularly in Europe. The accent on current production was reduced, but there was increased concern that systems should have long-term sustainability both environmentally and economically. For developing countries, the requirement is to develop systems that will increase production while avoiding the excessive losses to the environment that characterized the intensification of production in developed countries.

(c) Approaches to increase eco-efficiency

Eco-efficiency can be increased by altering (i) the method of production of individual crops or animals and (ii) the land-use system.

Other articles in this issue detail changes that may be made by altering the nature of particular crops and animals and their management. Briefly, in relation to the environmental concerns mentioned above, there is substantial scope for achieving genetic improvements in N and P use efficiency in plants and animals and achieving durable resistance to disease. Increased ability to predict the availability of nutrients from soil and manures (Jarvis & Aarts 2000) and better knowledge of threshold levels for weeds, pests and diseases provide the basis for precision farming with substantial

reductions in external inputs (e.g. Jordan *et al.* 1997) and reduced environmental losses. Methane emissions from ruminant animals are reduced when they are fed some forage species and there is also potential for reduction by manipulating the rumen fermentation and by animal breeding (Clark *et al.* 2005). Methane production per unit of animal product normally falls with increase in the level of animal performance, owing to dilution of the maintenance requirement.

This paper concentrates on effects from altering the system of land use. Along with the increase in intensification of agriculture mentioned above, there has been increased specialization both on individual farms and regionally. In England, for instance, the area of grassland used to support ruminant production in Norfolk in the east of the country in 2000 was only 27% of that in 1900, while in Devon in the west of the country the area of cereals in 2000 was only 64% of that in 1900 (calculated from DEFRA (2005a)), reflecting the climatic suitability for cereal production in Norfolk and for grass production in Devon. In Ontario, Canada, the proportion of mixed farms fell from 43% in 1961 to 18% in 1981 (Clark & Poincelot 1996).

Although in the early stages of food production, the production of crops and animals was separated, increases in human population led to a need to increase production per hectare. The response in the UK and much of the developed world from the Middle Ages was to develop mixed farming systems in which crop production was increased by added nutrients from animal manures and biological nitrogen fixation from legumes. The Norfolk 4-course rotation derived from the pioneering work of Coke started around 1730. The rotation consisted of turnips, barley, red clover and wheat. Nitrogen was fixed by the red clover and transferred to the subsequent crops. Turnips, red clover and natural grassland (not part of the rotation) provided feed for ruminants and the manure was applied to the arable crops, resulting in crop yields much higher than could be achieved from unmanured crops grown continuously. The availability of synthetic fertilizers, herbicides and pesticides at relatively low costs, coupled with high product prices, led, from the mid-twentieth century, to specialist crop production being adopted in much of eastern Britain, the area most suited to cereal cropping. Similar developments occurred through much of Europe, resulting in large areas having very low populations of grazing ruminants and the loss of the infrastructure needed for grazing livestock. It is now realized that these intensive specialist systems may not be truly sustainable.

In many developing countries, however, inputs of fertilizers and technical chemicals have remained at a low level. There are many circumstances, as discussed by Powell *et al.* (2004) for West African drylands, where crop and livestock production are still separated and there are large potential benefits both in terms of output per hectare and efficiency of resource use from effecting closer linkages between these two enterprises, as occurred in Britain with the 4-course rotation. This could provide an attractive and more widely applicable alternative to increased purchase of fertilizers using income generated by increased cash cropping on the farm.

Table 1. Key factors influencing the functioning of a rotation. (Adapted from Atkinson & Wilkins (2004).)

feature	impact and mechanisms
rotation sequence of crop species	speciation of nutrients (e.g. P and trace elements), availability of infective propagates of mycorrhizal fungi (MF), activity of microbial species, carbon inputs to soil, weed species; may also influence MF and microbes
intercropping	improved nutrient retention, slower release of nutrients to soil
crop and variety selection	needs of nutrients and pesticides, MF infection dependant
cultivations	MF infection, CO ₂ release from soil's N availability, especially in spring
nutrient management	losses due to leaching and denitrification; chemical species in soil, MF status, soil microbe communities
stock	changes to the timing of nutrients, increased protection of organic forms of nutrients; whether the key element of the rotation is an income-earning component or a 'fallow'

Section 2 considers in more detail the benefits that may result from alternations between crops and the association of crops with livestock in whole land-use systems.

2. ROTATIONS

Traditionally crop rotation has been important in conserving nutrients and minimizing losses. In conventional systems in the UK, the main purpose of the rotation is considered to be the management of soil-borne diseases such as take-all in cereals and nematode problems in potatoes (Atkinson & Wilkins 2004). In organic systems (and through most of the developing world), manipulation and control of nutrient supply and weeds are of major importance. Key factors influencing the function of a rotation are given in table 1, while table 2 indicates the reasons for including pastures in mixed farming systems in southern Australia. Mixed farming systems may, by reducing the reliance on individual crop or animal products, increase the stability of economic returns, but may produce substantial difficulties in managing these rather complex systems.

(a) Land use to maintain soil fertility

It is well recognized that soil organic matter content decreases with continued cultivation and cropping with arable crops, but increases under grass. Tyson *et al.* (1990) found that changing land use from more or less continuous cereals to pasture increased soil organic carbon from 1.2 to 1.8% in 10 years, with soil N increasing from 0.13 to 0.17%. The annual increments in soil C and N were 1000 and 75 kg ha⁻¹, respectively. With grass, not only does organic matter content increase, but there is also an improvement in structure, as indicated by an increase in the proportion of water-stable aggregates (Clement & Williams 1974). This will increase water infiltration, but detailed experiments on a well-drained sandy loam soil provided no evidence that the improvement in soil structure resulting from a grass ley was responsible for any of the increase in yield of subsequent arable crops (Clement & Williams 1974). With soils that have greater potential structural problems, these effects of including grass within the rotation may be critical.

Experience in southern Australia provides a clear example of dramatic adverse effects of specialist cropping on productivity and eco-efficiency, as discussed by Bellotti (2001). The replacement of native

perennial vegetation with annual crops (wheat and subterranean clover) results in a dramatic increase in deep drainage and aquifer recharge. Consequently, highly saline water may lead to salt accumulation in the rooting zone and reduce crop growth or cause crop failure. The inclusion of deep-rooted perennial species, such as lucerne, in a rotation will extract water to depth, reduce aquifer recharge and prevent increase in salinization. A similar approach using deep-rooted species is relevant to sustaining productivity of large areas of the world.

The extent of soil losses through erosion varies greatly with cropping system. Eder & Harrod (1996) quoted Danish research on sandy soils with a 10% slope which gave annual losses of 32, 6980 and 8400 kg ha⁻¹ for 2–3 year-old grass, wheat and fallow, respectively. They noted that the ability of grassland to resist erosion has long been used in soil and water conservation through the inclusion of grass in the rotation or the establishment of grass strips. The beneficial effects result from complete vegetation cover through the year, the infrequency of cultivation and the improvement of water infiltration associated with improved soil structure.

(b) Land-use systems to improve nutrient use efficiency

The use of legumes and animal manures to sustain crop production in mixed farming systems has already been referred to. There are many examples from temperate and tropical regions of benefits resulting from the inclusion of forage grasses and legumes in rotation with cereal crops. Clement & Williams (1974) in the UK found that the quantity of N in the soil increased by between 70 and 180 kg ha⁻¹ annually during the grass ley phase of a rotation. The increases were greatest when the leys contained legumes and were grazed; increases also occurred when large quantities of N fertilizer were applied to the ley, despite reductions in legume content. The yields of cereals following the ley varied by more than 50% depending on management of the ley. There was a close correlation between yield and the quantity of N mineralized from the soil in an incubation assay. In recent experiments in Belgium, Deprez *et al.* (2005) reported yields of wheat grown without fertilizer N of 3.2 and 5.2 t DM ha⁻¹ when following a 1-year ley of perennial ryegrass and 1-year ley of perennial ryegrass–red clover mixture, respectively. When fertilizer N was applied at 50 and

Table 2. Role of pastures in current and future cropping systems in southern Australia. (Adapted from Bellotti (2001).)

potential role	associated traits
reduce recharge	perennial deep roots summer growth
reduce weed populations prior to crop phase	plant root adaptation to potential subsoil constraints competitive herbicide tolerant
break life cycle of crop diseases	component of integrated weed management resistance to important crop diseases tolerance of crop diseases
biological nitrogen fixation	symbiotic competence N fixation in the presence of inorganic N
maintain soil organic carbon	ability to recover deep inorganic N root: shoot ratio C : N ratio of roots
compatible with current and new farming systems	ease of seed harvesting relatively soft seeded ease of removal prior to crop phase

100 kg ha⁻¹ to wheat following the grass with no fertilizer N, yields were increased to 4.6 and 6.0 t DM ha⁻¹, respectively, suggesting that red clover rather than grass was equivalent to the use of more than 50 kg N fertilizer per hectare to the grain crop. Advantages of using a legume were demonstrated in very different circumstances in Nigeria by Tarawali (quoted by Saleem & Fisher (1993)). Maize grain yields following 2 years of grass were 220 kg ha⁻¹, but were 1390 kg ha⁻¹ when maize followed 2 years of the legume *Stylosanthes*.

Farm livestock excrete some 50–95% of the N, P and K that they consume. Thus, recycling manures represents a large source of nutrients for the farming system. The composition of manure varies widely with the species of animal and its diet, the quantity of any added bedding material included in the manure and the losses that occur during storage, as discussed by Burton & Turner (2003). Further nutrient losses may occur on application to crops, particularly ammonia loss to the atmosphere and loss through leaching and particle flow should heavy rain follow manure application. MAFF (2000) estimated that some 90% of K and 30–60% of P in farmyard manure and slurry are available to subsequent crops, while for N the quantity available in the year following application varies from 10 to 55%, with further N becoming available in subsequent years. The application of manures to arable crops is a critical factor in crop production systems in which fertilizer is not used, including many traditional systems in the developing world and organic systems throughout the world. Possibilities for increased use of livestock manures are discussed later and present a major opportunity to increase eco-efficiency.

Green manuring, with crops being left on the soil surface or incorporated in the soil rather than being removed, may be used to improve eco-efficiency in the absence of livestock. Crops for green manuring are commonly catch crops of short duration planted between major crops. Such crops may contribute to the overall nutrient supply by retaining nutrients that would otherwise be lost. This applies particularly to autumn-growing crops taking up mineral N from the

soil at risk of loss from leaching. These crops may also restrict losses of soil (and P) through erosion by maintaining crop cover during winter. If the green manure crop is a legume, N may be added to the system through N fixation, in addition to any benefit through reducing N loss by leaching. Stopes *et al.* (1996) used red and white clover as green manure crops, with the legumes being mulched (cut and left on the soil surface). The quantity of N in the cut material from red clover was 371 kg ha⁻¹ in a single year. Winter wheat grown in the following year yielded 6.0 t ha⁻¹ after red clover compared with only 2.1 t ha⁻¹ after ryegrass. However, with red clover, 102 kg N ha⁻¹ was lost by leaching following cultivation and the establishment of the winter wheat compared with only 18 kg N ha⁻¹ with ryegrass.

Although green manuring can make a contribution to nutrient economy, this must be set against the monetary and energy costs of the establishment of the crop, and in comparison with the use of a forage crop by animals, there is no direct monetary return from the use of the land for growing the green manure crop.

With the use of green manures and fertility-building crops such as grassland, care needs to be taken to reduce the loss of nutrients during the transition to the main arable crops such as cereals, as noted above with red clover as a green manure crop. Ploughing and cultivation stimulate the mineralization of soil organic matter, putting it at risk of loss by leaching. These risks will be minimized if the subsequent crop is established with a minimum of cultivation and if the transition between crops occurs at a time when the subsequent crop grows rapidly and establishes a high demand for nutrients, reducing the nutrients that may otherwise be lost by leaching or denitrification.

(c) *Weeds, pests and diseases*

The effects of crop sequence and rotation on weeds, pests and diseases will not be comprehensively reviewed here, but it is clearly an aspect of great importance (see Entz *et al.* 2002). Before the advent of technical chemicals, the selection of crop sequences was of crucial importance in limiting damage by pests

and diseases. It still plays this role in organic systems, as discussed by Philipps *et al.* (2002), and may make a major contribution in integrated systems in reducing the number of chemical treatments required. Rotation in the UK is particularly important in limiting damage by nematodes in potatoes and root-borne diseases in cereals, owing to the limited economic efficiency of chemical alternatives (Atkinson & Wilkins 2004). Increased problems with herbicide-resistant weeds were noted by Entz *et al.* (2005) as one of the factors contributing to recent increases in the adoption of mixed farming in Canada.

(d) Low rate of adoption of mixed farming systems

Although there are great opportunities for increasing eco-efficiency by adoption of mixed farming systems, particularly those involving both crops and livestock, the trend, particularly in developed countries, has been for increased specialization and separation of crop and livestock enterprises. Atkinson & Wilkins (2004) considered that a major reason for the demise of mixed farming in Britain was that the costs of transferring animal manures from livestock enterprises to fields used for cropping became more expensive than purchasing fertilizer. They also highlighted the wish by farmers to reduce management complexity and the poor financial returns that have been experienced on mixed farms. In the Farm Business Survey in England, over the period 1996–2002, the mean annual net farm incomes (£k) were 17.8, 17.8, 13.8 and 10.9 for dairy, pig and poultry, cereal and mixed farms, respectively (DEFRA 2005b). Although the mean return was lowest for the mixed farms, there was an indication of a more stable income, with the mixed farm producing the lowest income in only one of the 6 years. The capital investment required to move from specialist cereal production to mixed farming may be high. This applies particularly to mixed farming involving grazing livestock, which requires secure fields and field watering systems as well as livestock housing and facilities for forage storage and feeding and is a major deterrent to the adoption of mixed farming. Recent substantial increases in the price of fertilizers and restrictions on total permitted inputs of nutrients will, however, increase the incentive to adopt such systems.

Mafongoya (2001) listed reasons for lack of adoption in sub-Saharan Africa of forage legumes, a key component of efficient mixed farming systems. These included (i) ecological conditions, (ii) traditional livestock production goals, (iii) labour and capital investments, (iv) land tenure problems, (v) weak extension services, and (vi) inadequate diagnosis and analysis.

(e) Requirements for increased adoption of mixed and eco-efficient systems

The BCPC Forum (2004) concluded that for producers in Britain to revert to mixed farming, it was essential that (i) it could be demonstrated unequivocally there was a clear economic advantage from linking crop and livestock systems, (ii) cost-effective ways of handling, transporting and incorporating animal manures into the soil be developed,

and (iii) the overall systems were managerially simple to operate.

Economic advantage could result from increased product prices, reduced production costs, increased overall production or from payments made for the environmental services provided. All these factors could apply with eco-efficient production.

The increase in demand for organic produce has led to the ability to sell organic products at premium prices. The rules for organic production limit the use of external inputs necessitating the effective use of on-farm resources, including techniques for efficient use of manures and exploitation of legumes. Entz *et al.* (2005) noted that over 30% of the land base on Canadian organic farms is devoted to forage crops, compared with less than 10% in conventional production, illustrating the closer linkage between crop and livestock production that commonly occurs with organic production. However, the restrictions imposed in organic systems, particularly in relation to mineral fertilizers, commonly lead to less efficient use of solar radiation and lowered yields. Premium prices for organic produce are thus a requirement for such systems to achieve economic viability. Frame (2002) provided further examples of instances where produce from particular methods of production command premium prices. In line with increased consumer concerns for the protection and enhancement of the environment, the examples include products from systems involving reduced pollution risk and increased farm biodiversity—characteristics of eco-efficient farming. There may be great opportunities for the promotion of the products from eco-efficient systems, but the proportion of food marketed in this way is currently very small and market forces are likely to mean that large price premia would not be able to be obtained should the production increase substantially, as has occurred in recent years with some products from organic systems.

There is some potential to reduce the costs of production by following eco-efficient land-use systems (through reduced inputs of fertilizers and crop protection chemicals), but the opportunities are probably greater from the use of precision approaches to reduce inputs in individual crop and animal enterprises.

Eco-efficient systems of land use are most likely to be readily adopted when they result in increases in productivity in either the short or the long term. This is most easily seen in developing countries where the introduction of forage legumes will result in increases in grain yields as noted earlier. This could be achieved through alternating cropping and grassland in ley farming or by the introduction and encouragement of legumes into fallows that are already part of the land-use system. Legumes will increase fertility by N fixation, and also increase both the quantity and quality of feed available for livestock with subsequent increases in manure production. Problems with salinization have already been mentioned. In this case, reductions in crop yield and crop failures provide evidence that present systems are unsustainable, but eco-efficiency can be increased by altering the cropping pattern to include more perennial crops, such as lucerne. There is a strong economic case for such changes not only in

areas currently badly affected by salinization, but also in areas where future salinization is indicated by increases in the water table. In the UK, however, although present intensive systems may contribute to pollution and inefficient use of resources, there is less evidence that the future productive potential of the land is being threatened by current methods.

The extent of atmospheric and water pollution associated with present intensive systems has, however, influenced legislation through, for instance, the EU's Nitrate Directive and Water Framework Directive. Large areas of Europe have been designated Nitrate Vulnerable Zones, with limitations to crop management and the quantity and timing of application of fertilizers and manures. By limiting inputs, this has produced a very direct incentive for the adoption of eco-efficient practices to maximize the efficiency with which permitted inputs are used.

Eco-efficient farming systems may attract subsidy payments from government, owing to their contribution to enhancement of the environment through improved quality of water or the atmosphere or through increased biodiversity. Agri-environmental schemes in the EU include subsidy payment for both the conversion of land to organic farming and maintenance of organic systems. Payment may also be made for the inclusion of small areas of cereals on grassland farms to produce mixed farming systems owing to benefits for wildlife, particularly birds.

Thus, through much of the world combinations of market opportunities, subsidies, legislative restrictions and a need to sustain the production potential of the land provide signals for increased adoption of eco-efficient practices. In many cases, this will involve increased complexity with the need for management skill to at least partially replace external inputs to achieve efficient production. With improvements in sensors and increases in computer power, there is, however, at least in developed countries, an increasing array of aids to help decision-making on the farm. This, coupled with the much higher level of education and training of today's farmers, should mean that superficially more complex systems should be able to be managed efficiently.

The problem of high capital requirements for the introduction of livestock on to specialist crop farms remains as a very potent obstacle for increased adoption of mixed farming *per se* as does the traditional separation of ownership of land and animals in parts of the world. The possibilities for area-wide approaches for integration of crops and livestock are discussed in §3.

3. AREA-WIDE APPROACHES TO INCREASE ECO-EFFICIENCY

Increasingly problems of eco-efficiency and environmental protection need to be addressed at a larger scale than the single farm.

For protection of water quality, a catchment-level approach is often most appropriate because the quality of water draining from the catchment will be influenced by the overall pattern of land use and water movement in the catchment. Thus, crops which may give substantial leaching of N or loss of P may still be part

of an acceptable pattern of land use, provided they occupy only a limited proportion of the catchment or are grown in low-risk areas (Rodda *et al.* 1995; Haygarth 2005). Ulén & Jakobsen (2005) stressed that only a few critical fields in a catchment may contribute a major proportion of the P load to water. Thus, it is crucial to identify such locations at high risk and apply specific managements to them. Buffer strips adjacent to watercourses may be used to limit the movement of soil particles and dissolved solutes to water, as discussed by Haycock *et al.* (1997).

An area-wide approach is clearly needed for preventing soil deterioration and salinization and for remediation when damage has already occurred, owing to the many factors operating over the whole catchment which will influence water tables, the movement of solutes and effects on production. Considerable success has been achieved in tackling salinization in Australia through voluntary Landcare Groups. Cooperative actions also provide the key for improving the use of common lands through the world, by, for instance, changing the control of grazing or agreeing the introduction of improved species. This may be difficult to achieve, but structures, such as Commoners Committees, often exist to facilitate debate on ways in which such resources can be managed.

Atkinson & Wilkins (2004) and Entz *et al.* (2005) both suggested that an area-wide approach may be appropriate for improving nutrient management and forage supply. Atkinson & Wilkins (2004) proposed linkage between specialist farms with the contract transfer of, particularly, manure between farms specializing in intensive animal production (pigs and poultry) and specialist crop producers. They calculated that manure recycled from poultry could, if used effectively, provide the total N required by 10% of the UK wheat area, with manure from pigs providing N for a further 5% of the wheat area. With this concept, individual farmers would remain specialists, but there would be increased movement of manures, and possibly feeds, between farms to increase overall eco-efficiency.

This is not a novel approach and Powell *et al.* (2004) referred to manure contracts between crop and livestock farmers being a feature of traditional systems in West Africa. Entz *et al.* (2005) described an example of area-wide integration in Western Canada. A company was formed in 1994 by four individuals who collectively owned 6000 sows and 900 steers with a crop and grassland area of some 6000 ha. Manure produced from the pigs was used to fertilize annual crops and forage land, with the cereals produced used in pig feeding and some of the forage land rented to local producers. This operation has continued to grow and in 2005 involved 40 000 sows. Entz *et al.* (2005) also described the integration of ethanol production from cereals with feedlot beef cattle production.

Such developments are in line with the suggestions of Steinfeld (1998) and Powell *et al.* (2004) that the evolution of crop–livestock integration begins with separate crop and livestock production (in subsistence farming), followed in sequence by integration (mixed farming), specialization and finally integration on an

Table 3. Summary of the two main types of crop–livestock integration in response to biological, economic and environmental constraints of specialized crop production. (Adapted from [Entz et al. \(2005\)](#).)

types of crop–livestock integration	major drivers for integration and location	requirements for successful integration
local, on-farm integration	soil sustainability on-farm salinity on-farm economic stress shift to organic production population pressure energy costs pest resistance	knowledge (education) labour local markets government support access to capital
area-wide integration	excess manure nutrients at farm scale widespread salinization necessity to share resources with urban areas opportunities to recycle manure nutrients through crops	cooperation between groups of specialized crop and livestock producers strong environmental legislation government support and facilitation technology (e.g. geographical information systems:GIS)

Table 4. Available nutrients in livestock manures and slurries in England in relation to requirements by crops and grassland.

	available N (kt)	available P ₂ O ₅ (kt)	available K ₂ O (kt)
supply from manures			
pigs and poultry	41.9	49.2	64.1
ruminants	49.4	54.9	202.1
<i>total</i>	<i>91.3</i>	<i>104.1</i>	<i>266.2</i>
requirement for nutrients			
crops	667.4	236.9	275.0
grassland and forage	748.0	118.7	245.6
<i>total</i>	<i>1415.4</i>	<i>355.6</i>	<i>520.6</i>
supply from manures as proportion of requirements	0.07	0.29	0.51

area-wide basis. [Table 3](#) summarizes the characteristics of the two main types of crop–livestock integration.

(a) Case study of manure use in England

The contribution that nutrients in manures could make to the requirements of arable crops and grassland in England is considered using information for 2004. Census data were used for livestock numbers and crop areas for the country as a whole and for the eight regions within the country ([DEFRA 2000a](#)). The production of farmyard manure and slurry per animal was taken from Brown (L. Brown 2004, unpublished data) and was based on standard figures for the UK. Nutrient composition and availability and crop demands for nutrients were taken from [MAFF \(2000\)](#). The P requirements were for soils with P index 2 and K requirements for soils with K index of 2i for arable crops and 1 for grassland; these figures represent the mean values for soils in England. For N applied to crops, the soils were assumed to be medium mineral soils with nitrogen status of 1. Grassland was assumed to receive 200 kg N ha⁻¹.

[Table 4](#) indicates that at an aggregate national level the supply of available N, P and K from manure (farmyard manure plus slurry, but excluding returns at grazing) was equivalent to 0.07, 0.29 and 0.51, respectively, of the total calculated nutrient requirements of arable crops and grassland. No region produced manure in excess of requirements, indicating considerable scope for effective use of manure without the need for long-distance transport. In England,

ruminant production is intimately linked with land for grass and forage production and it is probable that manure produced by that sector of agriculture will be used on the farm at which it is produced, with application principally to grass cut for conservation as silage or hay and to forage crops such as maize. Many large pig and poultry units are dis-associated from land for feed production and so the manure may be available for use by specialist cropping farms. Manure from pigs and poultry could contribute 0.08, 0.21 and 0.23 of the available N, P and K required by arable crops. This suggests that the best approach would be to limit the application of manure to any field to that required to satisfy crop requirements for P and K and to use mineral fertilizer to fulfil the requirement for extra N. The potential contribution from manure varied regionally supplying only 0.10 of the P requirements in North East England but 0.49 in North West England ([table 5](#)).

Although there are no regions with a manure surplus, it is clear that transport distances need to be short for manure use to make a real contribution to energy efficiency. Coefficients for energy use for the spreading and loading of manure from [Dalgaard et al. \(2001\)](#) and for manure transport from [Corré et al. \(2003\)](#) were used to calculate the energy required for different manures to be loaded, transported and spread for round-trip travel distances of 1, 10 and 50 km. The available nutrients in the manures were calculated in terms of fertilizer equivalents and the energy required for the manufacture and distribution of this quantity of fertilizer then related

Table 5. Supply of available nutrients in pig and poultry manures as proportion of crop (excluding grassland and forage crops) requirements for regions in England.

	N	P ₂ O ₅	K ₂ O
North East	0.03	0.10	0.12
North West	0.18	0.49	0.47
Yorks and Humberside	0.10	0.21	0.29
East Midlands	0.06	0.18	0.29
West Midlands	0.10	0.29	0.18
South East	0.06	0.18	0.20
South West	0.10	0.30	0.33
England	0.08	0.21	0.23

Table 6. Ratio of energy value of nutrients in manures to energy cost of loading, transport and spreading for different manures and transport distances.

		round-trip transport distance (km)		
		1	10	50
cattle				
manure	2.7	1.7	0.6	
slurry	1.5	0.9	0.3	
pig				
manure	4.8	2.9	1.1	
slurry	2.5	1.6	0.6	
poultry				
layers	8.7	5.3	1.9	
broilers	16.6	10.1	3.7	

to the energy cost for manure handling. Table 6 indicates the great effect of transport distance on the energy economy of using manure. While with a transport distance of 1 km, the ratio of energy value to energy expenditure was above 1 for all manures, when the transport distance was increased to 50 km, it was above 1 only for the relatively dry and energy-dense poultry and pig manures. This stresses the need for short transport distances if manure is to be moved by conventional road transport. There is however nearly 200 k ha within a 25 km radius of any point, giving in many cases a large demand for nutrients.

This analysis indicates considerable scope for manures to contribute to crop production and reduce the requirements for fertilizer inputs. The exact scope for improvement is not known owing to inadequate information on the current use of manures. Most manures are applied to land at present, but surveys in the UK (e.g. Smith *et al.* 2000) have indicated that farmers make little adjustment to the rates of fertilizer application to allow for nutrients provided in manures, in part owing to lack of confidence in crop response and difficulties in assessing the nutrient value of manures. Thus, the overall applications of nutrients may exceed crop requirements, leading to little response in production, but marked increases in losses to the environment. This will be exacerbated when fields close to livestock units receive manures at very high rates of application. The feasibility of increased reliance on manures has been increased by recent advances in techniques for the on-farm analysis of the quantity of available nutrients in manures and progress in

techniques for the efficient storage and application of manures, including band spreading and shallow injection (Burton & Turner 2003). Increases in price of fertilizers relative to product prices will also increase the incentive to make efficient use of manures.

4. CONCLUSIONS

The combination of crops spatially and temporally in land-use systems can make a major contribution to eco-efficiency with alternations and combinations of crops giving efficient nutrient use, particularly when legumes are included in the cropping pattern, and facilitating the control of weeds, pests and diseases. Incorporation of livestock in the system will give a wider range of crops, including grassland, and provide nutrients in manure. Catchment-scale management is needed to control loss of nutrients to water, restrict erosion and prevent land degradation through salinization.

There is, however, little evidence that the trend in developed countries to farm-level specialization is being reduced. In some circumstances legislation to restrict diffuse pollution may provide incentives for more diverse eco-efficient farming and in other circumstances price premia for produce from eco-efficient systems, such as organic farming, and subsidy payments for the provision of environmental services may provide economic incentives for the adoption of such systems. However, change is likely to be most rapid where the present systems lead to obvious reductions in the productive potential of the land, such as in areas experiencing salinization.

In other situations, eco-efficiency could be increased by the establishment of linkages between farms of contrasting type, particularly between specialist crop and livestock farms, with contracts for the transfer of manures and, to a lesser extent, feeds.

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