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Water pollution by agriculture

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Agriculture disrupts all freshwater systems hugely from their pristine states. The former reductionist concept of pollution was of examining individual effects of particular substances on individual taxa or sub-communities in freshwater systems, an essentially ecotoxicological concept. It is now less useful than a more holistic approach that treats the impacts on the system as a whole and includes physical impacts such as drainage and physical modification of river channels and modification of the catchment as well as nutrient, particulate and biocide pollution. The European Water Framework Directive implicitly recognizes this in requiring restoration of water bodies to 'good ecological quality', which is defined as only slightly different from pristine state. The implications for the management of agriculture are far more profound than is currently widely realized.

Keywords: eutrophication; Water Framework Directive; ecological quality

1. INTRODUCTION

It would be convenient if the component activities of agriculture could be simply and quantitatively related to their impacts on freshwater systems. This would be an ideal basis for creating legislation, for designing incentive schemes to optimize agricultural practice and for minimizing environmental consequences. However, it is far from possible. Both agricultural and freshwater systems are complex and the relationships between them make a mesh of many dimensions. Not least there are many sorts of agricultural system and a plethora of natural waters and communities. The entire land surface, much of which is agricultural, forms the catchment area for one or other river system and almost anything that happens on the catchment has an effect on the freshwaters. The relationship between catchment and receiving water is like that of a house and its waste bin. Most of the activities in the house are reflected in the contents of the bin. In 1979, the Royal Commission on Environmental Pollution (RCEP) published its Seventh Report, entitled *Agriculture and pollution* (RCEP 1979). Its preoccupations then are familiar still: pesticides, nitrogen fertilizers and organic farm wastes, but the concept of 'pollution' has become the much wider one of 'impact' as understanding has increased of how systems function. Simply to consider how substances emanating from agriculture affect receiving waters, the old concept of pollution, is to misunderstand most of the problem.

A scenario of a pristine landscape, in which settled agriculture is absent, is useful to create a baseline from which to assess the impacts of agriculture on receiving waters. Such a landscape would be covered by natural vegetation appropriate to the local climate and hence, through natural selection of its species, extremely well fitted to cope with the difficulties for plant growth of that particular place. Certain elements, particularly phosphorus, for reasons of its own properties of low solubility and the random accidents of formation of the planet in determining its absolute abundance, would be naturally scarce. So also would be available nitrogen, because its compounds are highly soluble and readily washed out into aquatic habitats but, under the naturally low oxygen concentrations that prevail in aquatic habitats owing to the polar nature of water and the covalent properties of oxygen, are readily denitrified to largely unavailable nitrogen gas. Other minerals might also be scarce, not so much in the young soils of the temperate zone where new rock debris was exposed abundantly only 10 000 years ago by ice, but especially in the ancient soils of the sub-tropics and tropics subjected to sometimes hundreds of thousands of years of leaching. Terrestrial vegetation in all cases has evolved systems (Raven *et al.* 2005) for conservation and recycling of scarce nutrients such that the water draining to headwater streams is extremely deficient in nitrogen and phosphorus and even in other relatively more abundant elements. This has been classically illustrated by the dramatic effects of forest clear-cutting on stream chemistry, when there is an immediate huge loss of many elements from the land surfaces (Likens *et al.* 1977).

In naturally vegetated, undisturbed landscapes, there is some loss of soil particles, but it is episodic and overall comparatively small, even in semi-desert. Again evolutionary mechanisms have selected for species that produce appropriate root systems, and for micro-organisms forming protective soil crusts that retain soil and nutrients. Of course, tree falls, fires, hurricanes, volcanic activity and other natural events will, from time to time, expose soil, and its erosion will produce the raw material of new sedimentary rocks ultimately to be formed in the ocean, but these events are occasional and the land surface is rapidly re-stabilized by a succession of species that ultimately reseal the soil surface. Disturbance has been caused by a million or more years of unconscious management, often by fire, by comparatively sparse populations of hunter-gatherer peoples and shifting cultivators, but the general principle of a

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minimization of loss of soil and nutrients prior to settled agriculture and development still holds. The waters draining tropical forests are little changed from rain water (Furch 1984) and where new lakes have been or are being formed in north temperate regions as glaciers retreat, an early phase of loss of nutrients and bases from the bare exposed catchments is rapidly succeeded by nutrient retention as vegetation develops (Engstrom *et al.* 2000). The pattern is one of decreasing base and nutrient status of undisturbed freshwater systems with time (Round 1961; Haworth 1969).

This conservation of mineral nutrients is twinned with an abundant provision of carbon by the natural terrestrial vegetation to the freshwater system. Carbon is not especially scarce on this planet. The ecosystems of headwater streams depend on the provision of leaf fall and woody debris for their pristine functioning (Harmon *et al.* 1986). Leaf detritus, rich in cellulose, lignin and tannins, but poor in other elements (the nutrient conservation mechanisms of the land vegetation translocate these back to the branches before abscission), is the prime energy source for streams that are naturally darkened by the forest canopy and in which photosynthesis is limited. In dense tropical forest, the headwater streams are revealed only where paths are cut across them, and in temperate forest, an undisturbed stream will be liberally littered by debris bridging the channel and retaining packs of leaves against the current. Hyphomycete fungi colonize the leaves, absorb nutrients from the tiny concentrations allowed to leach by terrestrial conservation mechanisms and build a more protein-rich leaf. A succession of invertebrates then shreds the leaves to reach this protein, producing finer particles as debris and faeces in the process. These become recolonized by micro-organisms and the food for invertebrate filter collectors and deposit feeders.

The invertebrate community is completed by predators and the food webs are topped by fishes and sometimes fish-eating mammals and birds and reptiles. Even much further downstream, a supply of carbon from the catchment may continue to be important. Fine particles feed the channel communities of flood plain rivers and dissolved organic matter from the catchment is increasingly suspected of providing perhaps half of the energy supply necessary to maintain the animal communities of pristine lakes (Hanson *et al.* 2004).

This flow of dependence is not entirely one way, however. Some of the nutrient requirements of the micro-organisms of headwater streams are provided by a loop that involves migratory salmonids, bears and riparian trees. Salmon populations, returning from the ocean to spawn, lose many members to exhaustion in the rivers on the way and are scavenged, in undisturbed north temperate systems, by bears. Stable isotope studies have shown that as much as 25% of the nitrogen of riparian trees comes from the ocean via salmon through bear faeces and excreta (Calman *et al.* 2002). Those salmon reaching the spawning grounds usually die after spawning and, in a pristine system, the fallen debris of riparian trees retains their carcasses. Subsequent *in situ* decomposition makes nutrients available in the headwaters for use by the micro-organisms that process leaves. In turn, these ultimately support the invertebrate food necessary for the salmon parr when the alevins have used up their yolk sacs. Connectance is very much a feature of pristine systems.

Terrestrial animals of the surrounding catchment, other than bears, may be integral parts of the system also. Wolves influence behaviour of their ungulate prey such that overbrowsing of willows (*Salix* spp) in and around the stream beds is avoided and habitat is maintained for beaver and small birds (Ripple & Beschta 2004*a*,*b*). Movements of large mammals across floodplains in the dry season bring nutrients in dung that are released as the water rises to support the survival of fishes migrating onto the flood plain in the wet season (Welcomme 1979). In Amazonia, there is a complex system in which fruits and seeds of forest trees support large fishes at high flood, while predation by caimans, piscivorous fishes and dolphins and their subsequent excretion again provides a supply of nutrients to support algal and invertebrate growth at a crucial time for the survival of newly recruited young-of-the-year fishes (Fitkau 1970; Goulding 1980, 1981; Goulding *et al.* 1996).

So far, only a small number of the dissolved substances that dominate the behaviour of natural aquatic systems have been mentioned. No one has yet fully analysed a natural water, but with the myriad of organic substances released in decomposition and root secretion, allelopathic substances produced by both land and aquatic plants, substances produced by the reactions of animals to the presence of their predators (Van Donk 2005) and a chemistry of inorganic ions and radicals that goes far beyond simplicity (Haygarth *et al.* 2005), there may be several thousands of substances in any natural water sample. Only recently has the significance of chemical messengers been described in unravelling the complexities of predator–prey relationships, but the emerging picture is of an enormous amount of chemical information being exchanged by organisms in systems that have developed and been refined to the changing conditions of natural environments by the testing to destruction of natural selection.

If the fundamental ecological features of undisturbed natural ecosystems are distilled out, they fall into four main categories. Firstly, there is a parsimony of available nutrients. Natural systems tie up nitrogen and phosphorus and tightly recycle them as scarce commodities. Available nitrogen and phosphorus are vanishingly scarce in most pristine waters. Secondly, there is a structure, characteristic of the particular climatic zone and in water bodies of their depth and area, which is complex and includes physical components (tree debris, geomorphological features) as well as the biological structure inherent in food webs, keystone species and the presence of top predators. Thirdly, there is connectivity, which includes unimpeded links among terrestrial systems in the catchment, river hydrology and access to the ocean. Finally, there is a sufficiency of size that gives resilience to change (refuges against local disturbance, for example) and sufficient territory for maintenance of large enough gene pools even of the largest animals to avoid inbreeding, and to maintain sufficient variation to cope with inevitable natural change in climate and other conditions. If these features are all in place, the system is self-maintaining, requiring no management by human beings. Only when it has been impaired is management needed to hold it together. Management is a manifestation of damage and considerable management is always needed in agricultural catchments.

2. AGRICULTURE AS KALI AND CERES

Kali is the Hindu goddess of destruction. Agriculture destroys natural, independent systems. It clears natural vegetation and substitutes, for the natural nutrient and soil conservation mechanisms, leaky systems in which nutrient losses to removed crops and by washout from disturbed soils must be continually replaced by fertilizer. It removes the supply of woody debris, eliminates top predators like bears and wolves in the interests of protecting domestic stock and may completely change the complex physical and biological structures of flood plain systems to promote drainage and irrigation. It may favour the increase of particular fish species through nutrient enrichment and cause major disruptions in food webs through altered predator–prey relationships (e.g. Vanni *et al.* 2005). It introduces novel and alien substances such as biocides to which there has been little time for evolution of defensive mechanisms. The bottom line is that notwithstanding the local instances of maintenance of biodiversity by traditional agricultural systems in maintaining ponds (Williams *et al.* 2004), wet meadows and fens (e.g. Wheeler 1980), agriculture has in no way had a positive net effect on the ecological functioning or biodiversity of receiving waters. Land use change for agriculture has been identified as the major threat to aquatic biodiversity (Sala *et al.* 2000).

Yet it has to be accepted that with a large human population that needs to be fed, agriculture is necessary. Ceres balances Kali as the highly desirable Roman goddess of the harvest. During the next 50 years, it is alleged that a further 10^9 hectares of natural ecosystems will be converted to agriculture resulting in two- to threefold increases in eutrophication problems (Tilman *et al.* 2001) and resulting in a conversion of approximately 5×10^9 ha of land from natural systems (Millennial Ecosystem Assessment Board 2005). This is about one-third of all lands, including deserts, tundra and Boreal forest, which are difficult or impossible to cultivate. The issue is to what extent can agricultural systems be redesigned to minimize the damage and continue to allow a substantial flow of extremely valuable natural goods from natural systems. These include atmospheric regulation, hazard control, water purification and storage, provision of pest control, natural grazing and timber production, and even cultural value. In recent years, a new approach to economics, in which environmental damage and environmental benefits have not been simply disregarded as ‘externalities’, has begun to replace the classical but flawed economics of Adam Smith. The difficulties of making valuations are great, but it seems incontestable that the values of natural systems are far from trivial (Costanza *et al.* 1997; Balmford *et al.* 2002) and may surpass greatly those of developed systems. It may be that for society as a whole, as opposed to an individual landowner or developer, many natural systems are most valuable in their undisturbed state, yet some of this value has to be traded to meet the food needs of a human population that has all but eliminated the natural mechanisms that in the past have, and in the future may again have, to limit it.

3. POLLUTION IMPACTS OF AGRICULTURE ON FRESHWATERS

In considering the comprehensive impacts of agriculture and how these can be mitigated, it is sensible to define both agriculture and impacts. Agriculture here means modification of the landscape for production of goods that are used for sustenance or market, whether eaten or used in other ways by settled human societies. It thus includes forestry, crop culture, biomass production for fuel and animal husbandry. There is a huge diversity in the intensity to which agriculture is carried out. In turn, ‘impacts’ on freshwater and marine systems means those that result from agricultural change of the landscape. These might include effects on water chemistry (nutrient loss; Haygarth 1997, 2005; Carpenter *et al.* 1998; Agouridis *et al.* 2005; James *et al.* 2005; Mehaffey *et al.* 2005; Olson *et al.* 2005) with consequent eutrophication and food web modification (Moss 1996; Pretty *et al.* 2003; Moss *et al.* 2004), biocide leaching (Hanazato 2001; Corsolini *et al.* 2002; Van den Brink *et al.* 2002; Cold & Forbes 2004; Traas *et al.* 2004; Christensen *et al.* 2005), suspended loads from soil erosion (Brodie & Mitchell 2005), alteration of the hydrological cycles (changed evapotranspiration rates and hence run-off and modification of river flows and irrigation water losses; Williams & Aladin 1991), effects of exotic species used, particularly in fish and crustacean culture, and physical modification of the habitat (channelization, channel modification, embankment and drainage; Raven *et al.* 1998). It is not easy to separate effects of agriculture from those of urbanization. Nitrogen and phosphorus leached from fields or animal dung have exactly the same effects as those produced by street drainage and human dung. In a sense, however, since urbanization depends on agriculture, the two are not separate, and just as agriculture is a social and cultural phenomenon (Pretty 2002) and not just a technological endeavour, its impacts on waters must be seen in the light of different ways of organizing and maintaining human societies. There may even be links between agricultural development and increases in disease vectors such as the freshwater naucorid bugs that appear, through their bites, to transmit *Mycobacterium ulcerans*, the cause of increasing incidence of Buruli ulcer in tropical Africa and Australia (Merritt *et al.* 2005). Links between irrigated agriculture and increased malaria incidence in the tropics are well established (Kebede *et al.* 2005). In its fullest sense, pollution is not just the addition of substances that damage or kill organisms, it is any man-made impact that increases the risk of damage to a natural system. Just as agriculture has comprehensively changed the face of the Earth, its impacts have equally profoundly re-wrought the nature of its waters.

4. PROBLEMS IN RELATING AGRICULTURAL ACTIVITIES TO ENVIRONMENTAL CONSEQUENCES

In an ideal world, it would be possible to take an individual agricultural activity, the spraying of a particular pesticide at a known dose rate, the application of a specific amount of ammonium nitrate fertilizer, the stocking of a specified cattle breed at a given density, for example, and measure precisely the effects of these on, respectively, the fecundity of a particular fish species, the growth of aquatic plants in a receiving lake or the extent of silting of a river stretch. The effects can be measured in a general way and modelled with varying degrees of uncertainty (Johnes *et al.* 1996; Van den Brink *et al.* 2002; Bowes *et al.* 2005; Westra *et al.* 2005; Van Wijngarden *et al.* 2005), but the sort of precision demanded by legislators and lobbies will never be attainable and this has been a major weapon used to delay regulation of agricultural activities.

The reasons for the impossibility of high precision are several. Firstly, controlled experiments under all conceivable conditions are impossible. It is feasible to set up selected demonstration experiments but only for limited periods and limited areas. Weather and landscape are infinitely variable and preclude comprehensive understanding (Haygarth *et al.* 2005). Secondly, most impacts of agriculture, indeed all except those involving specific biocides with no natural analogues, are paralleled by other human and sometimes natural activities. Animal and human excreta have similar effects (Hynes 1970) and are often discharged simultaneously into a river. Soluble inorganic nitrogen compounds come from mineralization of organic nitrogen in agricultural and undeveloped soils, from wastewater treatment works, from oxidation of nitrogen oxides in the atmosphere as well as from fertilizer run-off. Usually it is possible to partition these in a crude way using models but rarely, if ever, to tie down specific activities to specific consequences.

Thirdly, although ecotoxicology is a precise science in simple systems in the laboratory, its accuracy in determining ecological consequences is highly questionable. A particular substance may be shown in laboratory systems to have a particular threshold at which a test organism survives, or at which there is no observable effect. These thresholds are determined on a very restricted array of test species that are extremely tough, otherwise they would not be flexible enough to be used in laboratory systems. Nor are such organisms exposed to the risks of competition, predation and environmental fluctuation that they, and far more sensitive species, will be exposed to in nature and which may reduce thresholds enormously. Nor are they exposed to the much more complex chemical environment of nature where an array of potentially damaging substances may be simultaneously present. Despite increasing tendencies to test for ‘no environmental effect concentrations’ in mesocosms that are more complex than laboratory systems, though still greatly simplified, a huge literature on the potential impacts of biocides based on laboratory testing is thus largely useless in determining ultimate ecological impacts on freshwater systems.

5. AGRICULTURE AND ECOLOGICAL QUALITY IN FRESHWATERS

A reductionist approach has been the traditional way in which regulation of human activities has been handled, not least in the UK. The consequences have been the curtailing of some manifestly damaging activities, the use of highly potent pesticides such as organophosphorus compounds for example, or the release of raw silage liquor to streams, but a gradual deterioration in the ecological quality of UK and many European, freshwaters has not been avoided. Until 2004, it was claimed that the quality of British rivers was improving. This was because the nineteenth and early twentieth century impacts of discharge of raw or poorly treated sewage had, by the turn of the millennium, been largely controlled. The traditional way of assessing river quality has been to measure dissolved oxygen, biological oxygen demand and ammonium concentrations, all being indicators of gross organic pollution. Macroinvertebrate communities are also assessed and scored on a scale that reflects susceptibility of particular groups to organic pollution and deoxygenation. Some problems of gross organic pollution remain from illegal old sewage pipe systems in the cities, silage and slurry leakages and fish farms, but these are in the process of being cleared up.

The European Community’s Water Framework Directive (European Union 2000) was passed in December 2000 and has changed this view of substantial improvement of river quality. It requires all aquatic systems (subject to certain derogations) in Europe to be restored to ‘good ecological quality’ by 2015 and has completely rearranged the stage on which the drama of agriculture and its impacts is played out. The Directive’s target is not just chemical water quality but ecological quality and its emphasis is not on merely regulating discharge rates of potentially damaging substances at source but on the overall consequences of the complete gamut of human activities on the receiving ecosystems. It recognizes, as I have done in my definition of pollution above, that since simple cause and effect relationships are impossible to pin down precisely, an overview of more fundamental features and their linkages is necessary where activity in general is matched with consequences in general. The ultimate test is the ecological quality of the receiving system and member states must do whatever is necessary in modifying not just agricultural, but all their activities to achieve good ecological quality. The standards will ultimately be stringent, and the euphoria of progressively improving rivers burst in November 2004 when the UK Environment Agency announced that over 95% of British rivers and over 85% of all waters (including rivers, lakes, estuaries and coastal seas) would fail what emerged to be even very liberal standards of ecological quality.

The Directive requires first of all that a typology, a pigeonholing, of different sorts of water body (including coastal waters) must be created, largely on fixed geographical criteria (catchment size, area, depth, predominant catchment geology, altitude, etc.). For each of the types (ecotypes is the word used in the Directive), there must then be a determination of ‘high’ ecological quality, which is defined as the absence of other than very minor human impact. These scenarios may be determined by finding suitable examples, a near impossibility in a Europe dominated by agriculture and urbanization except in the most northerly latitudes, by palaeoecological reconstruction or by expert judgement or any combination of these. There must then be definitions of lesser ecological quality for each ecotype, based on a very large array of morphological, hydrological, chemical and biological variables (minimally approximately 40–50) on a scale of good, moderate, poor and bad. This system contrasts markedly with the list of half a dozen variables currently used in the UK to characterize rivers and none used statutorily to assess lakes and marine waters. The rub comes, however, with the definition of 'good' quality, to which the systems must be restored by 2015. 'Good' is defined as 'slightly' different from 'high'. 'Slightly' carries conventional dictionary definitions of trifling, of small degree or insignificant, and though we may expect, especially where political issues are concerned, some widening of this, it is clear that the consequences of the Water Framework Directive are very extensive indeed. To further its intentions, the Directive indicates that water must be managed on a whole catchment (river basin) basis and that the proper economic value of water must be paid. The implications for agriculture are very clear.

The Directive has a timetable for achievement of various stages, including restoration of aquatic systems to good quality by 2015 and, in 2004, the competent authorities in each member state were charged with assessing the risks that their water bodies would fail to meet the standards of good ecological quality. One difficulty in doing so was that there must be a general uniformity in standards set throughout Europe and a great deal of discussion and delaying action has ensued as several member states seek to keep the standards as low as possible so as to minimize expenditure and consequences for politically influential activities, including the agricultural industry. For the 2004 risk assessment, the UK Environment Agency was thus forced to use existing limited data that only marginally indicate ecological quality. It used individual chemical and structural measures, a reductionist approach, rather than features that perhaps a professional ecologist would regard as most reliable, and it set standards that may be appropriate for human health but which are of lesser relevance to ecological quality. Nonetheless, the failure rate, as indicated above, was of an order that would trigger complete overhaul of any other government department.

For variables particularly relevant to agricultural activities, river morphology and nitrate may be singled out. Most of the controlled river system (i.e. the river length, about one-third of the total, monitored by the Environment Agency and its equivalents in Scotland and Northern Ireland) in the UK has been engineered in the interests of flood control for cities and drainage of flood plains for agriculture. The remaining two-thirds of the river system, including all the headwater streams, has not previously been assessed but now comes under the Directive. The controlled river system has been described by river habitat surveys and found already to be seriously damaged, so it was no surprise that much of it failed simple criteria, especially in the lowlands. More surprising was the high failure rate on nitrate concentrations, even using a criterion of 10.5 mg NO_3-N l^{-1}, appropriate to risks of methaemoglobinaemia in bottle-fed babies but about an order of magnitude too high where ecological standards are concerned (James *et al.* 2005). Though phosphorus has been traditionally regarded as the most important nutrient influencing ecological quality in freshwaters, this view is changing as evidence accumulates for nitrogen limitation, especially in summer, in warmer, shallower and more lowland water bodies (Hameed *et al.* 1999), and the strong inverse link between plant diversity and nitrogen availability, evident from any fertilized meadow, has been revealed in the aquatic plant communities of freshwaters (James *et al.* 2005). The most diverse plant communities in shallow lakes in the UK are only half as diverse as those in the much less intensively farmed landscapes of Poland and achievement of just half the maximum UK diversity will require reduction of winter nitrate maxima in British waters to approximately 1–2 mg NO_3-N l^{-1}.

6. THE FUTURE LANDSCAPE OF GOOD ECOLOGICAL QUALITY AND ITS ACHIEVEMENT

Finding some compromise between maintaining agriculture and human food supply and conserving aquatic systems that also provide desirable goods and services through maintenance of a sufficiently diverse and functioning community will be far from easy and not attainable by cosmetic and local measures. Yet this is what the Water Framework Directive requires and what will be more generally required as western societies face the major impacts of climate change (Watson 2001), the end of the oil economy (Laherrere 2003; Anonymous 2004; Ehrenfeld 2005; Klett *et al.* 2005; Wilkinson 2005), a world population expanded by 33% or even 50% (Tilman *et al.* 2001) of 2005 numbers (6.4 billion) and the destruction of three quarters of the worlds' natural systems (Millennial Ecosystem Assessment Board 2005) by the middle of the twenty-first century.

If we return to the three concerns of the 1979 RCEP report, pesticides, nitrogen fertilizers and organic farm wastes, we may make some predictions. There has been much advance in controlling the use of pesticides, in developing compounds with shorter half-lives and in developing codes of practice. Leaching has generally been reduced in the first world (Powe *et al.* 1999), but the literature reflects continuing problems in the warm temperate regions and tropics (Dhar *et al.* 2004; Thiere & Schulz 2004).There are still biocide residues leaching to waters, sometimes directly through spray drift and persistent pesticides released decades ago are detectable in Antarctica and therefore presumably throughout the planet (Corsolini *et al.* 2002; Chiuchiolo *et al.* 2004; Montone *et al.* 2005). They may be transmitted through migratory fishes (Ewald *et al.* 1998) as well as by the atmosphere. Much of the literature, however, simply gives concentrations in water or in organisms. Experimental studies on consequences are scarce and since modern analytical technology is very sensitive, it is difficult to know whether the levels detected are significantly damaging. Biocides are, by definition, designed to kill living organisms, however, and the presumption must be of some damage where they are detected.

We can expect, however, that future technology will solve this problem, either through development of highly specific substances of infinitely low longevity or through culture or genetic engineering of specific parasites of weeds and crop pests. Though perhaps being the highest profile problem in the public mind, this is the most tractable. The real problem lies in nitrogen and organic matter, for there is nothing to be done to change either the fundamental nature of life itself or the fundamental properties of the elements that underlie it. Current agriculture is very leaky of nitrate. Despite much research in recent decades, it appears that approximately 25 kg ha^{-1} of nitrate nitrogen will inevitably leach from an intensive arable system (Ministry of Agriculture, Fisheries and Food 1999). Under British climatic conditions, this translates into a stream concentration of at least 10 mg NO_3-N l^{-1}. Waters in arable areas will thus always fail even the highly liberal criterion set by the Environment Agency in its 2004 risk assessment.

The solution of abandoning arable agriculture in the UK and importing all cereal needs is untenable, not least because we should anticipate major disruption in world trade as those four horsemen of the Apocalypse (climate change, end of the oil economy, population increase and habitat destruction) ride roughshod onto centre stage. Moreover, conversion to localized organic production systems is likely also to be desirable because estimates of the external costs (ranging from eutrophication and carbon dioxide emissions by transport to loss of biodiversity and landscape values) suggest reductions to only approximately 25% of the current ones of conventional agricultural systems (Pretty *et al.* 2005). The real cost of food is currently approximately 11.8% greater than the apparent cost allowed for these externalities.

In coping with the need for continued home production, nitrate problems and also the emerging one of phosphate leaking increasingly from saturated arable soils (Haygarth 2005) can be faced by using buffer areas that allow absorption of phosphorus and denitrification of nitrate. Wetland buffer areas are effective at removing nitrogen (Hey 2002; Kadlec 2005) but not phosphorus. Drier semi-natural vegetation seems necessary for the latter. The problem is that if water with 10 mg NO_3-N l^{-1} is emerging from the fields and a standard of lower than 2 mg NO_3-N l^{-1} is needed for the waters, simple proportionality dictates that only 20% of the existing arable area can remain in cultivation. Eight-tenths of it will be needed for buffer zones, even if they are completely efficient.

Twenty per cent of the current farmed area is unlikely to be sufficient to feed a UK population of 60 million people under present arrangements of food production, processing and marketing, with current dietary preferences. There are some temporary technological fixes, such as the application of dicyandiamide to inhibit nitrification of animal urine (Di & Cameron 2005). Some improvements can be achieved by movement back to former mixed systems (Bechmann & Stalnacke 2005; Bengtsson *et al.* 2005; Boody *et al.* 2005; Pimental *et al.* 2005). However, something so radically different (perhaps along the lines of 'rewilding' large areas; Taylor 2005) from the present as to be difficult for planners and politicians yet to conceive will become necessary if the aims of the Water Framework Directive are to be achieved in Europe, if equity of water use is to be accomplished in the developing world, where currently most water is used in commercial irrigation for crops sold in the first world (World Commission on Dams 2000), and if sustainable societies are to be created everywhere.

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