AGRICULTURAL PRACTICE AND THE EFFECTS OF AGRICULTURAL LAND-USE ON WATER QUALITY

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Abstract

The intensification of agricultural land-use and changes in farming methods in conjunction with new industrial technologies has made it possible to increase food production and cultivate land previously considered as unsuitable. This article examines the detrimental effects of this intensification and considers agricultural practices (conservation tillage) which aim to protect soils from degradation. The effects of agricultural land-use on water quality are considered in relation to excessive nutrients, application of agrochemicals, sediment input and contamination by heavy metals. National and European policies for water and soil protection are discussed.

Keywords: agriculture, water quality, soil water protection, policies.

Introduction: modern farming methods and soil degradation

Over the last few decades there has been a global trend towards intensification in agricultural land-use and changes in farming methods have been paralleled by new industrial technologies. This has enabled the production of large amounts of cheap inorganic fertilisers in order to meet increasing demands for food and other agricultural products (Benites & Vaneph, 2001). Accordingly, the pattern of fertiliser consumption has changed dramatically (Fig. 1). Furthermore, through modern advances in technology, there has been a marked geographical expansion of agriculture regardless of the suitability of the land, and likewise the development of new hardier crop types has made it possible to cultivate under marginal environmental conditions (Altieri & Anderson, 1992; Altieri & Rosset, 1996).

Modern farming methods, which often are referred to as conventional farming, are very efficient and produce high crop yields but can have a profound impact on the environment (Benites & Vaneph, 2001). Modern farming methods employ large and highly efficient machinery, hence old

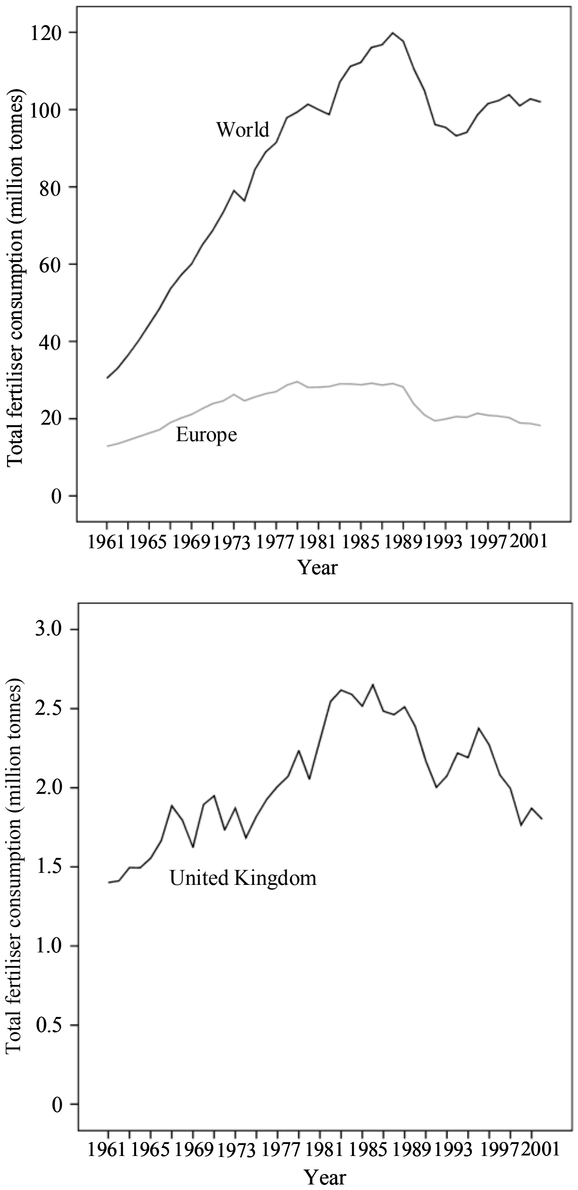

FIG. 1. Fertiliser consumption between 1961 and 2001. Note the difference in scale of the two graphs (data obtained from FAO, 2008).

field boundaries in the form of hedges have been removed in many parts of the UK and Europe. This has led to a considerable increase in the average field size and a shift towards monoculture on large areas of land, with fields left bare for considerable periods during the season. In addition, crop rotation has become a less common practice and fields are rarely set aside for a fallow recovery period (Blunden & Curry, 1985; Arden-Clarke & Hodges, 1987; Robinson & Sutherland, 2002).

As part of modern farming practices, seed beds are tilled, i.e. the soil is ploughed using specialised machinery in order to reduce the bulk soil to a fine crumb structure (tilth). Tilling has a long history and is beneficial because it disrupts compacted areas, and aerates and loosens the soil. The mixing of nutrients and organic matter promotes micro-organisms and worms which in turn maintain soil fertility. Historically soils were tilled using human labour or hoofed animals pulling a plough. Nowadays, however, machinery has become so specialised that some farmers rely entirely on leased machinery that is shipped in from various parts of the world for the planting season (farmer, personal communication). Most commonly, modern conventional tillage involves repeated tillage operations (as many as seven separate field passes). A typical primary operation, using a mouldboard, turns the top soil over to a depth of 25 cm. This method cuts through and fragments the bulk soil, and buries crop residues and pest weeds. The organic matter content of the soil is briefly increased by the inversion of the soil but ultimately the decomposition of the organic matter is hastened due to an acute but relatively brief increase in microbiological activity (Stockfisch et al., 1999). The secondary operations involve disks and harrows and have the purpose of further fragmentation of the soil to obtain a desired aggregate size to create a good seed-to-soil contact for fast and uniform seed germination (Hadas, 2004).

Conventional tillage has a major impact on soil structure and frequently does not lead to the desired promotion of crop development, due to structural degradation of the soil (Huwe, 2002). The extent of soil modification and damage to the soil depends largely upon soil type, organic matter content and in particular soil moisture levels and timing of ploughing. In general, poorly structured soils with a high percentage of silt and low percentages of clay and organic matter (i.e. sandy soils and sandy loam soils) are more at risk from mechanical damage. Timing of cultivation is also of paramount importance; poorly drained soils will suffer increased surface and sub-surface compaction, also wheelings from tractor tyres tend to be deeper and tramlines (severe localised compaction) are more likely to develop in wet conditions (Arden-Clarke & Hodges, 1987). Despite the potential negative effects, it is not always possible for the farmers to be flexible in the timing of field runs due to physiological characteristics of a crop type, which determine the length of a crop season and/or the timing of nutrient and herbicide applications. The negative consequences are disaggregation of soil structure, increased soil erosion, oxidation of soil organic matter and disruption of the functions of soil organisms (Arden-Clarke & Hodges, 1987; Holland, 2004). Such adverse effects on soil structure and associated non-sustainable losses of nutrients and organic matter have led to a reliance on improved crop varieties and extensive use of agrochemicals to fertilise crops and control weeds and pests. Farmers get caught in a cycle where degrading soils force them to increase procedures such as tillage runs and applications of agrochemicals, often above recommended levels, to correct for the continual decline in soil fertility, which in turn causes further degradation to soil health (Altieri & Anderson, 1992; Parish, 1992; Altieri & Rosset, 1996).

As a result of agricultural intensification, many countries, including Britain, face problems with soil degradation and loss of top soils due to wind and water erosion, which in the past have been largely prevented by the use of less intensive farming methods (Arden-Clarke & Hodges, 1987; Chambers & Garwood, 2000). For example, in the USA it is estimated that erosion is about 17 times greater than the rate at which soil is formed and that 90 % of the cropland in the USA is losing soil above its sustainable rate. Similarly, an increasing number of reports state that soil losses are increasing above sustainable levels across Europe (Arden-Clarke & Hodges, 1987; Chambers & Garwood, 2000; Holland, 2004; European Commission, 2006a).

Conservation tillage

The effects of intensive agriculture on terrestrial and aquatic systems are well documented and widely recognised as undesirable (Arden-Clarke & Hodges, 1987; Altieri & Anderson, 1992; Altieri & Rosset, 1996; Schulz & Liess, 1999; Schilling & Wolter, 2001; Hart et al., 2004; Hunt et al., 2006). Specialised farming systems based on monocultures are increasingly vulnerable to pest outbreaks and despite the fact that inputs of fertilisers and agrochemicals are still on the rise, there is a global trend towards a decline in crop yields (Altieri & Anderson, 1992; Altieri & Rosset, 1996). In an attempt to halt and reverse the negative impacts of modern farming on the environment and national economies there has been a move towards more sympathetic and sustainable farming practices.

The term ‘conservation tillage’ covers a range of agricultural practices, which aim to protect soils from degradation processes by minimising changes to soil composition, structure and biodiversity. In general, conservation tillage includes any practice that reduces, alters or eliminates soil tillage and leaves the soil surface with protective plant cover, at least to some extent, throughout the year. The techniques include direct sowing

(no tillage), reduced tillage (minimum tillage), non- or surface incorporation of crop residues, and establishment of cover crops.

The reported beneficial effects of conservation tillage include reduced water and sediment run-off, improvement to organic matter content and protection of soils from further degradation. Typically, production costs are also reduced under conservation tillage due to fewer field passes (Harper, 1996; Rosner & Klik, 2001; Schreiber et al., 2001; Honisch et al., 2002; Holland, 2004; Tomer et al., 2005). The capacity of conservation tillage to improve water quality in adjacent water courses was also demonstrated in a Canadian study where the results suggested that samples from conservation tillage streams yielded a greater variety of insects but fewer taxa of molluscs, annelids and crustaceans than did samples from conventional tillage streams (Barton & Farmer, 1997).

Reduced soil tillage minimises surface evaporation and plant residues preserve soil moisture. Consequently, many farmers in semi-arid and arid areas of the world (e.g. North and South America, Africa and Australia), where preservation of soil moisture is of paramount importance and/or where extreme weather events cause soil erosion, have adopted conservation tillage methods (Holland, 2004). In contrast, in more temperate climates typical of much of Europe, farmers are less inclined to adopt reduced tillage methods. Soils under conservation tillage management are likely to stay wetter and colder for longer periods during spring. This in turn can lead to delays in sowing, reduction in the length of the growing season and ultimately affect crop yields. In addition, there are concerns about weeds, pest-insects and crop diseases that may proliferate under reduced tillage, potentially increasing the need to apply herbicides and insecticides to the fields (Witt, 1990; Harper, 1996). Nevertheless, sensible farming practices such as crop rotations, employing crop types adapted to climatic conditions, smaller fields which support higher crop diversity, and re-establishment of hedgerows and fallow areas as shelter for wildlife, can help alleviate problems with plant pests and diseases. Set against any disadvantage, there is ample evidence that de-intensification of farming is beneficial for the environment. It is crucial, however, to adapt soil tillage techniques to local topography, soil and climate conditions (Arden-Clarke & Hodges, 1987; Carpenter et al., 1998; Holland, 2004).

Effects of agricultural land-use on water quality

Contamination of water bodies by excessive nutrients and agrochemicals

Catchment characteristics such as geology, soil type, hydrology and climate, but in particular land use, are all important determinants of the physical and chemical features of a specific water body (Allan, 1995). Due to agricultural intensification over recent decades, vast amounts of fertilisers and agrochemicals have been applied to agricultural land in order to achieve maximum productivity. Excessive nutrient concentrations not recovered by the crop plants end up being washed into adjacent aquatic systems where they may cause problems such as eutrophication (Altieri & Anderson, 1992; Altieri & Rosset, 1996). In the UK there has been a marked increase in the percentage of length of rivers with good water quality in the early to late 1990s, coincident with the general decrease in nutrient consumption on farmland (Fig. 1, Fig. 2). The trend has levelled off in recent years but biological and chemical water quality is still improving. In contrast, rivers with high phosphate (> 0.1 mg L^{-1}) and nitrate (> 30 mg L^{-1}) concentrations have only declined slightly over the last ten years. Over 25 % of the total length of rivers had high nitrate concentrations and 50 % of the total length of rivers had high phosphate concentrations in 2005 (Bingham, 2008) (Fig. 2). Much of the excessive nutrients can be attributed to agricultural land-use and it has been estimated that 61 % of nitrates and 40 % of phosphates in English waters are derived from agricultural inputs (Defra, n.d.). Compared to non-agricultural land (e.g. woodland, moorland and heathland) average leaching losses of nitrate can be up to four times higher from cultivated fields (5 to 16 kg N ha^{-1} and 23 to 75 kg N ha^{-1}, respectively) (ADAS, 2007).

Agriculturally induced water pollution may occur from point sources (e.g. manure storage tanks, feedlots, overflows, tile drains) as well as through diffuse pollution from farmed land. The nutrients and agrochemicals applied on the fields may reach adjacent water bodies via overland flows and subsurface flows during precipitation events or, at a slower rate, reach surface water bodies through groundwater discharge. Main flow paths differ between nutrient species. For example, phosphorus transport occurs mainly bound to soil particles as overland flow whereas dissolved agrochemicals and nitrogen can enter aquatic systems via overland flow, subsurface flows and groundwater flows (Pionke et al., 1999; Defra, 2002b; Hart et al., 2004). Surface run-off of polluted water and sediments is seasonally variable and peaks are closely related to rainfall events. Under UK climatic conditions, peaks in nutrient flows and erosion events can be observed during winter and early spring when precipitation is high and there is little crop cover to take up mobilised nutrients (Chambers & Garwood, 2000; ADAS, 2007). An increased supply of nutrients, especially phosphates and nitrates, can cause algal blooms and excessive growth of aquatic macrophytes in both freshwater and marine ecosystems (Biggs, 1996; Carpenter et al., 1998; Holland, 2004). The increased productivity due to substantial nutrient inputs leads to increased bacterial decomposition of dead organic matter, which in turn, is the cause of declining oxygen concentrations.

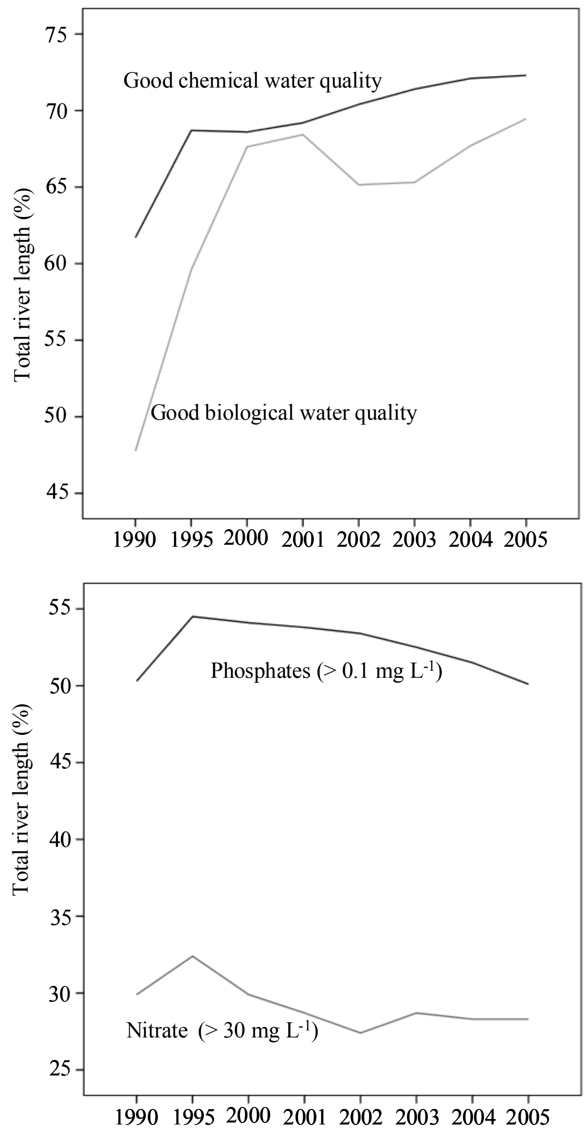

FIG. 2. Total length of rivers with 'good' biological and chemical water quality as defined by the Environment Agency's General Quality Assessment (above), and high phosphate and nitrate concentrations (greater than 0.1 mg L^{-1} and 30 mg L^{1}, respectively) (below) for England and Wales, 1990–2005 (data obtained from Bingham, 2008).

Problems with increased input of sediments to water bodies

Streams and rivers receive sediments from surface and bank side erosion. Storm events in particular contribute to elevated concentrations of suspended sediments in water courses. Research has shown that during storm events, 60 % to 96 % of the suspended sediment was derived from surface sources as opposed to bank-side erosion and that sediment yields were up to ten times greater from agricultural catchments than forested catchments (Allan et al., 1997; Walling, 2005). Increased erosion rates from tilled fields can cause excessive deposition of fine sediments in receiving streams that block interstitial spaces and river-bed gravels which are important spawning habitats for many fish species. Sediment deposition also contributes to changes in channel morphology and flow regime. Additionally, suspended sediments reduce light penetration, scour surfaces and may interfere with feeding mechanisms, drift rates and respiration of macroinvertebrates and fish (Doeg & Koehn, 1994; Wood & Armitage, 1997; Relyea et al., 2000). Ultimately, excessive sediments and associated nutrients in aquatic systems lead to a decline in habitat heterogeneity, loss of keystone species and the general degradation of an aquatic ecosystem (Holland, 2004).

Contamination of water bodies by heavy metals

Apart from nutrients and sediments, water quality may also be burdened by heavy metals which originate from organic and inorganic fertilisers, pesticide applications and irrigation water (Nicholson et al., 2003). Soil structure and chemistry determine heavy metal solubility and bioavailability. In general, plant uptake and leaching losses are small compared to the total heavy metal loads entering the soils. In the long term there is a potential for slow accumulation of toxic elements in the soil, which may lead to negative effects on plant growth and the function of soil organisms. Ultimately, heavy metal related changes to the quality of soils may lead to mobilisation and leaching of the accumulated toxic elements to groundwater reservoirs and adjacent freshwater systems (Saviozzi et al., 1999; Nicholson et al., 2003; Reiher et al., 2004).

National and European policies

Soil protection

Soil erosion and water pollution by agrochemicals, caused by the expansion of agricultural land, is a global problem and the increased awareness of the negative effects of modern intensive farming methods are reflected in recent national and European policies (European Commission, 2006a; IUGS, n.d.). Since 1990 the Common Agricultural Policy (CAP) of

the EU (European Union) has put emphasis on sustainable and environmentally sound farming. National agri-environment schemes have been supported by the EU since 1992 and the CAP reform in 2003 was based around the decoupling of paid subsidies and amounts produced. Farmers no longer receive subsidies on the basis of how much they produce and they are financially rewarded if they comply with environmental, animal welfare and food safety standards (European Commission, 2004).

There have been several international environmental agreements with influence on soil protection including the Kyoto protocol, the Convention on Biological Diversity, the United Nations Convention to Combat Desertification and the Alpine Convention. Within this context, the sixth Environment Action Programme (2002–2012) of the EU called for a development of a thematic strategy for soil protection. The strategy was adopted in 2006 comprising a communication on the principles of the Community's soil protection policies, a proposal for a Soil Framework Directive and an environmental, social and economic impact assessment of the strategy (European Commission, 2006b). In 2002 the UK government launched a strategy for sustainable farming and food, followed in 2004 by the introduction of the first soil action plan for England and the UK Catchment Sensitive Farming Initiative (Defra, 2002a; Defra, 2004a; Defra, 2004b).

Water protection

The Water Framework Directive (WFD) came into force in December 2000 and is the most significant water policy legislation currently applicable to the EU (European Parliament & Council, 2000). The WFD integrates and updates a number of existing water policy legislations such as the Urban Waste Water Treatment Directive (1991), the Nitrates Directive (1991) and the Drinking Water Directive (1998). The WFD provides, through River Basin Management plans, a framework for the assessment and improvement of the ecological status of all water bodies. In contrast to former legislation, it extends to the whole aquatic system; rivers, lakes, groundwater, transitional and coastal waters. The main goal for the WFD is to achieve 'good' ecological status of all waters by 2015 and to ensure that there is no deterioration in the status of waters of good quality (European Parliament & Council, 2000; Logan & Furse, 2002).

Currently, reduction of diffuse pollution, particularly phosphorus and nitrogen but also pesticides and heavy metals, is one of the key elements in achieving cleaner waters. However, many of the EU countries have largely focused on identifying and reducing the impacts of point source pollution (Carpenter et al., 1998). Consequently, non-point source pollution derived from extensive areas of arable land has become an important contributor to the overall pollution of water bodies in these countries and many of the goals outlined in the WFD are closely linked to the establishment and maintenance of sustainable land-use practices in order to protect farmland against further degradation. Adoption of conservation practices in Europe, however, has generally been slow for two main reasons. Firstly, in the past, the Common Agricultural Policy of the EU provided no economic incentive for de-intensification and sustainable farming; on the contrary, it encouraged highly productive farming systems. Secondly, important key players in the European Union such as Germany, France and Great Britain failed to recognise that they were facing significant problems due to the negative impacts of intensive arable cultivation (Arden-Clarke & Hodges, 1987). A recent EU-Life project, 'Soil and Water Protection using Conservation Agriculture in Northern and Central Europe' (SOWAP), aimed to develop practical field-based solutions for farmers and to provide scientific and economic evidence of the viability and effectiveness of conservation-oriented land management practices in order to support European agricultural and environmental policy decisions (Anon, 2007; SOWAP, 2007). The project was conceived in an effort to close the gap between increasing interest in sustainable soil and water resource management in recent environmental policies and the lack of policy-relevant research on soil health. The project also aimed to highlight the potential for adapting farming methods in Europe to protect soil and water from further degradation.

In addition to regional research-based policy programmes such as SOWAP there are organisations such as WOCAT (World Overview of Conservation Approaches and Technologies), established as a global network, whose mission is to provide tools that allow soil and water specialists to share knowledge in soil and water management which will support them in making decisions in the field and at the planning level (WOCAT, n.d). Much of this knowledge is not well documented and hard to find and WOCAT facilitates the free flow of information to interested parties.

In the future, the proliferation of environmental policies, research and the collation of knowledge will hopefully improve the ways in which sustainable farming interacts with water resources to promote and reach overall environmental quality standards.

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