

SCOPE 51 - Biogeochemistry of Small Catchments

16 Agricultural Impacts in the Northern Temperate Zone

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16.1 INTRODUCTION

In early history, much of the Earth's surface in the temperate zone was covered by forests and steppes. The more fertile and accessible lands were gradually converted to agriculture, while less productive areas in the hills, on slopes or on sands were left forested. The former were more intensively and more frequently managed and thus the agricultural soils developed a deeper topsoil layer. Forest soils remained shallower in comparison and are considered to be more pristine.

The scientific study of agricultural areas started with research based on the plot approach. This shaped the ideas about the nutrient requirements of crop plants and enabled an evaluation of the relative productivity of certain cultivars of valuable plant species under comparable conditions. It also produced information on the movements of nutrients and other compounds within the soil and subsoil. Lysimeters gave supplementary data on leaching. Plot observations, even when integrated temporally or spatially, do not fully reflect the scope of impact on the environment of agricultural activities. For instance, ammonium pollution from excessive agricultural application of nitrogenous fertilizers is damaging nearby forests in The Netherlands and elsewhere (Nihlgård, 1985). Visualization of the agricultural plot as part of an input-output system led to investigation of higher scale biogeochemical fluxes. Especially

through comparison of natural and artificial (highly managed) systems, ecological ideas have spread into agricultural research, resulting in catchment studies of arable lands and, eventually, the genesis of the agroecosystem concept (Lowrance *et al.*, 1984).

16.1.1 AGROECOSYSTEMS AND CATCHMENT STUDIES

Agroecosystems are characterized by massive inputs and outputs of materials and energy, and replacement of many internal natural controls with external artificial controls of sociological, political and economic nature. Under modern agricultural practices in industrialized countries, maximization of output from agroecosystems in the form of crops is frequently accompanied by high losses of solids (erosion), liquids (soil solution leaching) and gases (denitrification, ammonium volatilization). As Woodmansee (1984) pointed out, for purposes of comparison, the most important properties of natural ecosystems are their abilities to maintain or accumulate nutrients and persist through time. Thus, losses must be counterbalanced by high inputs of energy, fertilizers and other chemicals (herbicides, pesticides, growth regulators) in order to maintain the fertility and prolong the life of the system.

Early efforts utilizing catchment studies include Harrold's and Edwards's (1972) comparison of three agricultural catchments with different tillage practices. They found that the no-tillage catchment exported virtually no soil during an extreme storm event, while the poorly managed conventional catchment lost vast amounts of soil by erosion in the same episode. In a similar study by Jones *et al.* (1977), the quality of runoff water from three conventional agricultural catchments was compared; differences were attributed to soil and hydrological characteristics; all three catchments exported substantial quantities of sediments, nitrate and phosphorus. Analysis of sediment cores from a pond in an agricultural catchment has been used to assess the transition from early agricultural practice to modern agroindustrial techniques by tracing the history of eutrophication and metal and soil inputs (Brugam, 1978). Using a more fully ecological approach, Roberts (1987) details a mass balance study of nutrient cycling on a lowland agricultural catchment in England by describing input and output measurements and including rationalization of some estimates of gaseous losses and off takes due to cropping and animal consumption. Using similar techniques, Cooke and Cooper (1988) evaluated N flux in a New Zealand pasture catchment and Roberts *et al.* (1989) compared two pasture catchments manipulated by different agricultural regimes.

Integration of ecological concepts into agricultural research has led to the exploration of a variety of alternative methods to improve crop yield while minimizing the magnitude of energy and nutrient inputs. Catchment studies are an important tool for the quantification of effects of different treatments in terms of loss through erosion and leaching. In general, these studies are considered as building blocks of more complex models of landscape structure. Comparisons between catchments can illustrate the positive and negative effects of different land usage ([Figure 16.1](#)). This chapter discusses some aspects of land use and agricultural impact on biogeochemistry as shown by small catchment and other types of ecological studies, with respect to practical and responsible management policies for the future.

Most of the information presented is relevant to the temperate zone. This prevents direct application of these results to tropical countries, but extrapolation of temperate data and models to tropical systems might be useful for planning future work. We feel the relative scarcity of small catchment data from developing countries to be a major gap both in small catchments studies and particularly in the theoretical rationalization of agricultural production in the tropics. For obvious reasons, the catchment approach is limited in very arid areas with irregular rainfall, but such regions are typically unsuitable for most agricultural production.

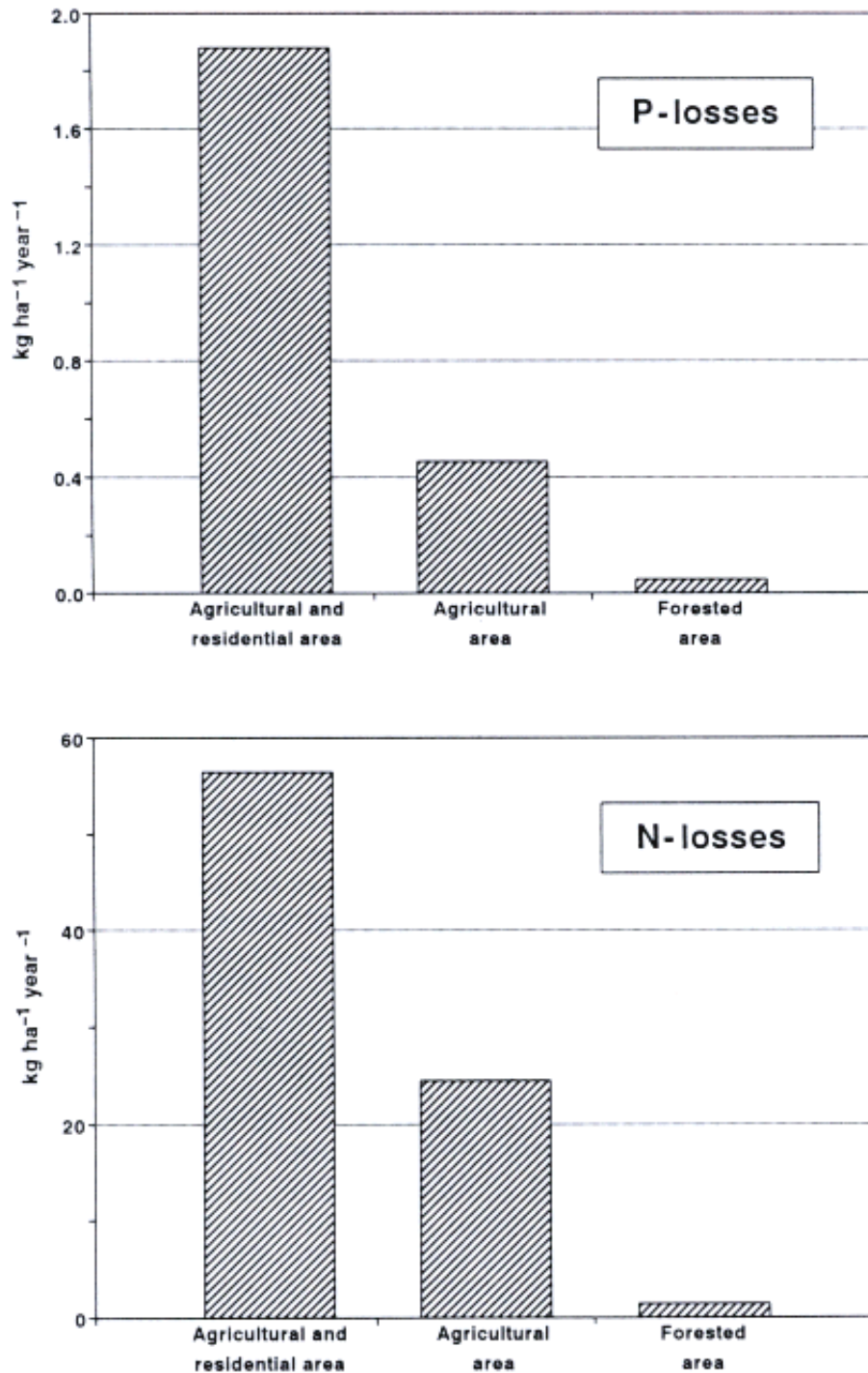


Figure 16.1 Nitrogen and phosphorus losses ($\text{kg ha}^{-1} \text{ year}^{-1}$) from different sub-catchments within a mixed-use catchment in South Sweden (data from LRF, 1988).

16.2 SOIL PHYSICAL MANAGEMENT

Alteration of a soil's physical structure and properties necessarily changes its biological and chemical characteristics as well, and may dramatically disrupt the biogeochemical cycling within and through a catchment. When ecological homeostasis is disturbed, abiotic factors may drive the system toward substantial losses of materials through erosion until new controls are established (Woodmansee, 1984). Massive export of carbon and nitrogen generally follows cultivation of virgin land, but the C/N ratio seems to be maintained (Reinhorn and Avnimelech, 1974). The amounts of C and N exported depend on

the cultivation practices and initial soil characteristics (Bauer and Black, 1981). Thus, maximization of agricultural output must be accompanied by increased inputs to and/or greater controls of the soil, both of which are added expenses, or reconciled with practices which utilize natural inputs and controls and/or decrease the levels of undesirable outputs.

The literature reporting agricultural research on tillage practices is extensive, but most experiments are based on a plot approach and involve characterization of the soil profile and assessment of soil water quality using lysimeters. Profile reconstruction is a technique used to assess changes in organic matter and inorganic nutrient content and morphological properties of cultivated soils in comparison to an adjacent uncultivated native soil with respect to erosion, crop removal and mineralization (Kelly *et al.*, 1988). Borders of agricultural catchments are usually defined by artificial drainage systems rather than the morphology and geology of a basin (Roberts *et al.*, 1986), so these catchments may be viewed as large lysimeters more than catchments.

16.2.1 EFFECT OF DIFFERENT TILLAGE PRACTICES

The type of tillage employed to prepare a site for planting causes significant changes in soil physical properties. Biogeochemical cycling is also affected. Current practices often involve deep ploughing and disc harrowing of the soil to provide a good seedbed and this increases availability of plant nutrients through stimulation of mineralization and repression of denitrification. It also offers good protection against weeds, especially stoloniferous weeds. This type of cultivation can, however, deeply disrupt the natural soil structure and the synchronicity of plant/microbial interactions, increasing the potential for erosion and leaching losses. Practice of minimal tillage is in general much less disruptive of the soil structure and requires much smaller inputs of fossil fuel energy (Lockeretz *et al.*, 1981), though it often requires greater use of chemical herbicides to control weeds. Minimal tillage complements multicropping by saving much time and resource loss between harvest and replanting (Phillips *et al.*, 1980).

Roberts *et al.* (1989) compared runoff concentrations of N and P between two sub-catchments in upland Wales, each manipulated by a different pasture improvement scheme. The sites differed principally in the degree of cultivation: the first, Nant Iago, was disc-harrowed before planting, the other, Nant-y-Moch, was spike-seeded. Nant Iago showed massive export of nitrate after fertilization in the first year but not in subsequent years, in contrast to Nant-y-Moch, suggesting that disc-harrowing promotes N export, perhaps through stimulation of mineralization processes by aeration. There were insignificant differences in ammonium concentrations and variation in P could best be explained by the type of fertilizers applied.

Long-term changes in the chemical and physical properties of soils under stubble cultivation and shallow tillage (to 10 cm depth) have been contrasted to conventionally tilled soils on a range of soil types. In Sweden, Rydberg (1986) found that minimally tilled soils generally had greater compaction in the middle topsoil (causing increased hydraulic conductivity and thereby decreasing infiltration), improved aggregate stability and decreased evaporation. The compacted layer might have functioned as a chemical bottleneck, effectively concentrating P, K and organic matter at the surface, while reducing these in the middle and lower topsoil; no evident changes were detected in the subsoil. Powlson and Jenkinson (1981) found insignificant differences in total organic matter content (as opposed to distribution), biomass, ATP and labile N in comparisons of ploughed and direct-drilled soils; a fourth soil, richer in clay, had a higher ATP value in the direct-drilled soil.

Despite the mechanical resistance presumably offered by a compacted, and thus denser substrate in the upper soil layer, Chaney *et al.* (1985) found greater root mass for spring barley under 20 cm depth in their long-term minimally-tilled plots. Rydberg (1987) found that root development was hampered under shallow tilled soils, though the effect was less pronounced in soils minimally tilled for ten years than in soils minimally tilled for three years due to improved natural soil structure (i.e. development aggregates

and the proliferation of cracks, pores and worm channels). Concentration of nutrients in the upper topsoil may exaggerate the effect by decreasing the need for an elaborate root structure.

Minimal tillage techniques leave a crop residue on the surface which reduces moisture loss and provides a continuous decomposition substrate, a gradual input of organic matter, and subsequent gradual nutrient release with low leaching. Stubble mulch practices or other coverage practices reduced the loss of carbon and nitrogen compared to bare fallow cropland on soils of different textures (Bauer and Black, 1981); in some cases nitrate leaching may be reduced by more than 50% (LRF, 1988). Weeds, crop residues or winter crops physically constrain the movement of water and wind across the soil surface, reducing erosion, especially during storm events. Contour ploughing in conventional systems has the same objective, but is undoubtedly less effective at most sites, particularly those with sloping or uneven terrain.

The incorporation of straw residues into the surface layer of the soil increases soil pore size, which increases water infiltration and retention and decreases evaporation by reducing capillary transport; it also decreases evaporation by promotion of slaking in the uppermost soil layer, which creates a crust (Rydberg, 1987). Besides other benefits, amelioration of porosity by amendment with straw, sand or wood chips may also decrease denitrification by minimizing anoxic conditions. Denitrification is of significant importance in agricultural soils because N, whether of natural origin or applied, is often a growth-limiting factor for plants. Deep ploughing tends to reduce denitrification by aerating the soil, although minimal tillage practices increased oxygen concentrations in soils during wet winters due to natural processes of soil aeration (Dowdell *et al.*, 1979).

Consideration of the tillage time is important to prevent erosion and leaching of nutrients. Ploughing during the late autumn leaves the soil exposed to wind and water, thus facilitating erosion. Autumn ploughing also stimulates mineralization of organic nitrogen and, as a result, large quantities of nitrate are leached into groundwater over winter; Cameron and Wild (1984) reported a loss of 100 kg N ha⁻¹ over two winters at two ploughed, unplanted sites in England.

16.3 CHEMICAL MANAGEMENT

As practised, chemical management such as application of mineral fertilizers and pesticides ameliorates agrolandscapes and compensates for atmospheric deposition to the soil surface. Intensive application of agrochemicals (>500 million t year⁻¹ worldwide and about 300 kg ha⁻¹ year⁻¹ in Europe alone) and other anthropogenic pressure on biogeochemical cycling of biologically significant elements and water has sharply increased. Many studies of the consequences of chemical management on nutrient cycling exist at the plot scale but only a few have been carried out in small catchments. It is necessary to combine both approaches to agricultural catchments in order to understand the productive and ecological consequences of intensive chemical managements.

The influence of chemical and crop managements in Chernozem sandy arable soils on nutrient cycling was studied in plot experiments over five years by Korotkov and Kravchuk (1988). Four crop rotations (lupins, rye, potatoes, oats) were under study. Nutrient content of harvested crops and residues varied, P being higher in cereal and potato crops than in residues, K highest in potatoes, N in lupins. Overall nutrient removal for the rotation was 1364 kg ha⁻¹, with a return of 983 kg ha⁻¹ in residues. Moisture infiltration was significant but fluctuated according to crop type and season, being greatest with row crops and during autumn, spring and rainy summer periods. This also influenced N flux, mainly nitrate. Ca was most subject to leaching, followed to a lesser, but significant, extent by Mg and K. Phosphorus was little affected.

The C and N budgets of four agroecosystems with annual and perennial crops, with and without N fertilization were studied by Paustian *et al.* (1990). In field plots at Kjettslinge near Uppsala over five years, annual C and N budgets were calculated for the following systems: (a) barley without fertilizer; (b) barley with 120 kg N ha⁻¹ year⁻¹; (c) *Festuca pratensis* with 200 kg N ha⁻¹ year⁻¹, and (d) *Medicago sativa* ley without fertilizer. Annual net primary production (including roots) was 2400, 4800, 7400 and 7900 kg C ha⁻¹ year⁻¹, respectively; annual organic C inputs to the soil were 1500-1800 kg C ha⁻¹ year⁻¹ in (a) and (b) and 3500-4000 kg C ha⁻¹ in the leys. Total N inputs and outputs balanced in fertilized barley but decreased by 40 kg ha⁻¹ year⁻¹ in non-fertilized barley. Total N increased in (c) by 90 kg ha⁻¹ year⁻¹ in plant standing crop and 30 kg ha⁻¹ year⁻¹ in soil. Denitrification rates were lowest and leaching losses were highest in barley plots. Estimated microbial production was 50% higher in the leys than in the barley systems, in correlation with a higher C-input and a higher soil respiration rate.

Management practices such as tillage and crop residue placement, cropping system, irrigation practices, weed control, etc., can influence fertilizer N efficiency (Power and Broadbent, 1989). Consequently, fertilizer use efficiency can and does vary greatly. All these variables affect soil microbial activity and N mineralization-immobilization rates. Leaving crop residues on the soils surface, for example, creates a cooler and wetter environment which affects activity of soil microorganisms and results in differential effects on N cycling and availability.

16.3.1 MAIN NUTRIENTS: NITROGEN AND PHOSPHORUS

Estimating N input and removal from crop production systems is one of the first considerations when evaluating chemical management practices which minimize N leaching and contamination of groundwater (Schafer and Fos, 1989). It may not be necessary to quantify precisely all N inputs and outputs from crop production systems before sound management practices can be developed, provided producers are aware of the need to minimize nitrate leaching.

A positive correlation between nitrate and runoff was shown in a small (10 km² agricultural catchment area (Pytz, 1989). Studies of fields in 1987 and 1988 showed relationships between nutrient losses, crop succession and fertilization. The limited uptake of water by barley led to increased nitrate leaching when winter precipitation was more than 300 mm. Increased phosphate leaching was observed after the harvest of winter barley. Differential nutrient uptake by broad-leaved and cereal crops with the same fertilization level was reflected in the variations in nutrient losses.

Conventional and organic crop management was studied on two 4-ha fields with gleysol soil by comparing nitrate leaching in drain water (Feige and Röthlingshoffer, 1990). Nitrate concentration showed seasonal patterns with the greatest variation in the winter season. In an average rainfall year, 25% of the drain water runoff occurred during the summer months but nitrogen losses during that time were below 20%. NO₃⁻ concentrations from the organically farmed field were consistently lower than those obtained under conventional farming, the highest values being 110 and 180 mg l⁻¹ NO₃⁻, respectively. In the course of a year, 50 kg ha⁻¹ year⁻¹ were leached from the plot under conventional management while only 25-30 kg N ha⁻¹ year⁻¹ were lost by organic farming. Organic farming proved less detrimental to groundwater than conventional farming.

Agrochemical application was examined in some catchments in the Chesapeake Bay region of the USA to determine its effects on surface and groundwater resources. It was shown that concentrations of both nutrients and pesticides in surface runoff are highest when runoff occurs soon after application. Pesticides are not conserved in the soil and therefore are not leached in high quantities during winter groundwater recharge. Groundwater concentrations varied among the four herbicides considered,

suggesting that restricted use of more mobile compounds may be an effective way to control environmental contamination. Soluble N remains in the root zone until after the growing season, then leaches readily into the groundwater. Cereal grain cover crops can remove significant amounts of soluble N (up to 100 kg ha^{-1} from the root zone) and therefore offer a readily available method for decreasing the transport of nitrogen from agricultural systems while possibly enhancing levels of productivity (Staver *et al.*, 1987).

Delivery of phosphorus from heavily fertilized cropland to Lake Ontario was studied by Longabucco and Rafferty (1989). Monitoring of several sites for a year showed that runoff during late winter and early spring was a more important hydrologic factor in annual P loading from the mucklands than either total precipitation or total runoff for the year. Surplus P leached in subsurface runoff accounted for the high dissolved P load coming from muck cropland. As much as 72% of the dissolved reactive P and 39% of the total P entering the lake from this creek could be due to P losses from the muck cropland 65 km upstream.

The influences of agrochemical applications on catchments and the effects of irrigation on toxic substances in surface and groundwater were described in a 15- year biogeochemical investigation in moderate and tropical climatic zones (Bash kin, 1989). In regions under intensive fertilizer application and irrigation farming, it was found that the content of various compounds of N (NO_3^- , NO_2 , NH_4^+), P (ortho- and polyphosphates), K, Ca, C and micronutrients greatly exceeded World Health Organization (WHO) limits. Increased agrochemical flux to soil components was the main source.

A study between 1976 and 1985 examined the extent and direction of N and P fluxes in the upper reaches and right-bank tributaries of the Desna River in the Ukrainian Polesie region with the aim of assessing possible ecological damage from agricultural operations and fertilizer use. Water samples were taken during spring and summer in seven small catchment areas under varying degrees of cultivation and compared to a forested area. Results indicated a direct dependence of N and P content upon degree of cultivation and fertilizer inputs. Losses of fertilizer N from 30 to 65 kg ha^{-1} inputs averaged 2.2%, those of P, 0.9%, from 10 to 70 kg ha^{-1} inputs. Compared to background concentrations, there was 42-91% more N and 8-69% more P in watercourses draining farmed land. Ammonium-N entered the rivers mainly in surface runoff, nitrate in groundwater. P was present in surface runoff through substantial flushing of organic P compounds from peat bogs and marshy areas. The forest site was more stable with, on average, 60% less N and 47% less P being removed (Matuchno, 1988).

Data from several groundwater monitoring studies indicate that nitrate concentration in shallow groundwater beneath agricultural fields with extensive fertilizer application routinely exceeds 10 mg l^{-1} . The results of these studies indicate a need to alter agricultural practices. Possible alternatives for minimizing N leaching from agricultural catchments include expert systems, soil and plant tissue testing, use of organic nutrient sources and cover crops.

16.3.2 PESTICIDES

Pesticides strongly influence agrolandscape productivity. Monitoring their behaviour in the agrolandscape must include the synergistic or antagonistic effects of mineral fertilizers and heavy metals on pesticide transformation and flux. Pesticide, nutrient and water flow rates were monitored in six subsurface drains in a slowly permeable silt loam soil of southeastern Indiana, USA. Garbofuran, atrazine, cyabazine and alachlor were detected, mostly after chemical application in the spring. The relative amounts of pesticides detected were consistent with adsorption isotherm data for these pesticides (Monke *et al.*, 1989).

Ahlsdorf *et al.* (1987) described groundwater contamination following agricultural application of dichloropropane, atrazine, aldicarb and simazine, which are characterized by high mobility and relatively low persistence in topsoil. Aldicarb and its metabolites were shown to have a much longer half-life, by almost two years, in groundwater than in topsoil. It is considered likely that permissible levels will be exceeded where atrazine is applied to over 20% of land overlying sandy subsoil. Neary and Michael (1989) studied the effect of sulfometuron methyl on groundwater and stream quality in coastal plain watersheds. The herbicide was applied by ground sprayer at a maximum labelled rate of 0.42 kg ha⁻¹ to a 4 ha catchment. Residues were detected in streamflow only seven days after treatment and did not exceed 7 mg m⁻³, but were not detected in stormflow or sediment. Residues did not appear in a shallow groundwater aquifer, <1.5 m below ground surface, until 203 days after application. Lack of herbicide residue movement was attributed to low application rates, rapid hydrolysis in acidic soils and water, and dilution in streamflow.

16.4 BIOLOGICAL MANAGEMENT

Simulation of natural ecosystems may enhance consistent, long-term agricultural productivity. This stems from a more flexible response to short-term fluctuations in environmental conditions beyond the control of the farmer, as well as the conservative nature of ecosystems over the long term. Agroecosystems with increased biotic diversity generally require less input of fertilizer, pesticides, herbicides and mechanical energy because the biota themselves fulfil the input requirements and provide controls against each other and changes in the environment. These systems may be more stable and sustainable than monocultural systems currently in widespread use in industrialized countries.

At the extreme, commercial agricultural practice seeks to reduce plant diversity to a monoculture, the production of a single strain of a desired crop grown in isolation with a particular, ideally suited management regime. In actual fact, some form of mixed cropping (crop rotation, intercropping and/or varietal diversification) occurs, not least for allowing the farmer some freedom from the vicissitudes of the marketplace and the environment (Francis, 1986).

Rotating crops diminishes the depletion of certain crucial resources by using plants with different nutrient requirements. Ideally, rotation can replenish certain nutrients which may be of benefit to the next crop; fodder plants, usually legumes with N-fixing bacterial associations, are often ploughed back into the soil as "green manure" between two main crops. Other effects include control of such herbivores and pathogens as nematodes and fungi by alternating the hosts to which they are specialized (certain cultivars or species cannot nourish certain soil pests). Farmers in America's 'corn belt' often rotate maize and soybeans for both soil rejuvenation and insect pest control (Lockeretz *et al.*, 1981). Drawbacks of crop rotation include the need for a larger array of specialized equipment, as well as multiple ploughings and harvests, which disrupt natural soil structure.

Intercropping is the practice of growing two or more crops in the same field at the same time to take advantage of beneficial species interactions, reduction of moisture loss, soil stabilization and weed repression. Mitchell (1984) presents evidence from a number of studies demonstrating superior yields of mixed crops to monocrops for several different systems in industrial countries, as well as examples from traditional mixed cropping systems in India. Without fertilizer amendment, mixtures of cereals and legumes produced greater forage yield than either grown alone, and improved cereal yield on the same plot the next year (Osman and Nersoyan, 1986). Even in monocropping systems, benefits may accrue by less expenditure of energy and chemicals for weed control, as weeds themselves may be considered as a type of intercrop. Some fix N or serve as a nutrient reservoir in systems which are nutrient-poor. Crossley *et al.* (1984) speculate that weeds occupy space which could be used by better competitors or even that weeds and crops may do more than just tolerate each other, a mutualism may in fact exist

(Maun, 1974). Some weed species are important to predators of insect herbivores (Altieri and Whitcomb, 1979); diversification assists in inhibiting insect damage for over 200 plant species (Andow, 1983). A comparison of intercropped and monoculture agroecosystems showed significantly more macroarthropod predator activity against insect pests (Brust *et al.*, 1986).

When plants are grown on the land continuously, certain physical benefits to the soil arise from a constant canopy and root colonization: a decrease in wind and water erosion and increased input of organic matter, which promotes soil friability and stabilization of clay-humus complexes and an increase in water-holding capacity of the soil which, in turn, reduces leaching. Biological effects include habitat improvement for soil flora and fauna and provision of a year-round food source (carbon substrate) for organisms, which may reduce leaching by maintaining the synchronicity between microbial mineralization and immobilization and decomposition and plant uptake. Mycorrhizal networks may also benefit from a lack of disruption. Stimulation of microbial activity may improve the entire soil community and thus influence certain chemical and physical factors. Mulching increased populations and metabolic activity of bacteria, actinomycetes and fungi 2-6 times by increasing the moisture content in soils used for corn production in Nebraska (Doran, 1980a). Increased microbial and enzymatic activity facilitate mineralization, but immobilize significant quantities of N during the growing season and increase denitrification (Doran, 1980b).

Increasing animal diversity within a catchment would reintroduce a number of natural controls to agricultural systems. Numbers of earthworms, including deepburrowing species, were higher in minimally tilled plots compared to ploughed plots, and population size increased with each successive year after conversion to minimal tillage (Barnes and Ellis, 1979). The volume and number of earthworm channels were greater in no-tillage vs. ploughed plots and were generally more effective for water infiltration because of larger numbers of surface ports (Ehlers, 1975). Large soil animals such as millipedes, termites and beetles were virtually eliminated from ploughed and grazed plots in Western Australia due to soil compaction which reduced soil permeability, friability and content of organic matter and nutrients (from faecal pellets), in comparison with virgin and no longer used soils (Abbott *et al.*, 1979). Reduced compaction as a result of minimal tillage would probably foster increased populations of these animals, invigorating the entire soil community. In a comparison of four barley and pasture cropping systems in Sweden, Andren *et al.* (1988) found insignificant differences in abundance and biomass of nematodes, microarthropods and earthworms in the soil.

Farms organized on biodynamic principles have greater occurrence of parasites, predators and antagonists of insect and fungal pests (Wagstaff, 1987; Brust *et al.*, 1986). Herbivory is usually considered negatively but is tolerated from pollinators, but low levels of grazing (as opposed to total eradication of insect populations) may actually stimulate primary production (Hilbert *et al.*, 1981). Harper (1987) described the New Zealand practice of grazing sheep and goats together; since these animals prefer legumes or grasses, respectively, they assist in maintaining an ideal species balance in pasture vegetation in terms of nutrient consumption and replenishment.

Use of organic fertilizers, reduced pesticide input, low impact tillage and, especially, crop rotation with higher proportion of fallow, pasture and forage crops relative to cash crops, may lead to greater production of large animals on many farms (Lockeretz *et al.*, 1981). Since nitrate migration into groundwater is much slower from organic than mineral N sources (Ott *et al.*, 1983), optimization of manurehandling systems would contribute to increased plant nutrient retention, reducing the need for inorganic fertilizer application, but also somewhat increase fossil fuel energy input (Stonehouse and Narayanan, 1984).

16.5 WATER MANAGEMENT

Water management in agriculture aims to optimize water supply and nutritional conditions for the crops while minimizing environmental impact. Practices may include drainage, irrigation and stream and riparian zone management. All of these practices will have important consequences for water quality, water pathways and stream response time to rainfall.

Irrigation aims to maintain the soil moisture levels between a minimum level and the field capacity while assuring optimal conditions for the crop. Excessive irrigation can result in water percolation and associated rise in groundwater. This may lead to contamination of groundwater with fertilizers and agrochemicals. Excessive irrigation may also lead to excessive water percolation, salinization of the soil and increased soil erosion. Irrigation management aims to schedule onset, frequency and amount of water per application to maximize yield while using energy and water resources efficiently. This may be achieved through simulation models to determine optimum irrigation scheduling (e.g. Algozin *et al.*, 1988).

Drainage is carried out to remove excess water from agricultural fields to a main drainage system or groundwater. There are a variety of drainage systems used in agriculture such as ditch drains, mole drains, pipe drains and drainage wells. These may increase transport not only of water but also agrochemicals and nutrients to water courses or groundwater as the water will bypass the lower soil mineral horizons which have a large capacity to buffer solute concentrations (Deal *et al.*, 1986; Tobin and Rajagopal, 1990). Drainage has also been used to reclaim wetlands for agricultural purposes (e.g. Ahl and Andersson, 1988). The effects of this wetland drainage will be an increase in rate of nitrogen mineralization, sulphur oxidation and substrate decomposition rates (Grootjans *et al.*, 1985; Lieffers, 1988). This may result in a release of, in particular, ammonium, nitrate, sulphate and organic acids (Kenttämies, 1980). This increased anion mobilization may result in increased leaching of cations such as calcium and magnesium from nutrient-rich peats or protons and aluminium in nutrient-poor acid peats. Water from drained peats may also be enriched in phosphorus and potassium (Hornung *et al.*, 1988). In contrast, gaseous emissions (N_2O , CH_4) will be decreased due to the lowering of the water table and an increase in aeration.

The transfer of agricultural chemicals, fertilizers and drainage waters to water-courses may be controlled by effective stream and riparian zone management (Lowrance *et al.*, 1985; Petersen *et al.*, 1987). Stream management such as channelization has been carried out in the past to increase drainage and regulate water levels. This, however, has resulted in a loss of streamside vegetation and native riparian ecosystems and therefore removed the buffer between non-point sources of pollution such as agricultural fertilizers and the stream. These wetland riparian ecosystems act as effective nutrient filters due to uptake by near-stream vegetation, sediment deposition and, in the case of nitrogen, microbial denitrification. Drainage will increase runoff rates and reduce residence time in the riparian alluvial and peaty soils which have large water storage capacities, thus reducing the time period for these soil and vegetation uptake processes to occur. The nutrient uptake capacity of wetland riparian zones will decrease over time and is not limitless (Wieder *et al.*, 1988). The use of riparian zones on both metal and pesticide transport is more variable depending on the metal and chemicals involved (Lowrance *et al.*, 1985; Hemond and Benoit, 1988). The reduction of wetland riparian zones as a result of intensive agricultural practices can adversely affect stream water quality and consequently fish stocks. Restoration may be encouraged through return to native vegetation or management to improve both productivity and their nutrient storage capacity, for example through the planting of fast-growing trees such as willow (*Salix*) or alder (*Alnus*).

16.6 INDUSTRIAL EFFECTS

There have been many studies on the effects of agricultural practices on small catchments, but very few

studies on the effects of direct industrial activity on catchments and on agriculture in catchments.

Direct industrial effects may be defined as those arising from industrial activity occurring within the boundary of the catchment, as opposed to those transported from elsewhere in the form of deposition of atmospheric pollutants, a topic considered elsewhere in this volume. The main types of industrial effects are:

1. Physical disruption of the soil/plant system during civil engineering operations, such as opencast coal mining, mineral extraction and road construction.
2. Contamination of the soil/plant system, such as heavy metal mining and smelting operations.

16.6.1 PHYSICAL DISRUPTION

Physical disruption of the system has been shown to have a significant effect on physicochemical and biological characteristics of the soil/plant system. The best documented examples come from studies of areas mined for coal by the opencast method. During opencast coal mining, topsoils, subsoils and overburden are stripped, stored for three months to ten years in large mounds, and reinstated on the worked area, which entails complete disruption of the soil/plant system. This results in soils which are compacted and very poorly drained (Tomlinson, 1980).

Studies have shown that peak drainflow rates on restored opencast sites significantly exceed those on normal agricultural land (Trafford and Twocock, 1972; Hodgkinson *et al.*, 1987), and can result in a greater load of total suspended solids in water receiving runoff from these sites. Scullion and Mohammed (1986) have also demonstrated that in soils reinstated for up to ten years after opencast mining, water runs off the surface rather than infiltrating. King (1988) demonstrated that reinstated areas had high bulk densities, few macropores or biotic channels and the soils were weaker than in undisturbed areas. Harris and Birch (1989) showed that soils disturbed by opencast mining had less total nitrogen than undisturbed controls, and there was evidence to suggest that this nitrogen had been lost by volatilization of ammonia, denitrification and loss nitrate by runoff. This amounted to a loss of 675 kg N ha⁻¹ year⁻¹, which would have a major effect on waters received from areas disturbed by such activity.

There is also evidence of deleterious effects on the biology of soils in catchments disturbed by civil engineering. It has been demonstrated that the combination of stripping, storage and reinstatement results in a marked change in the size, composition and activity of the soil microbial community. Harris *et al.* (1989) showed that there was a decrease in the microbial biomass in disturbed soils to as little as 7% of the value of an undisturbed control area. Since the microbial community has a central role in the cycling of nutrients and contributes significantly to structural stability of soils, this represents a significant compromising of any soil/plant system developing in these catchments.

16.6.2 CHEMICAL CONTAMINATION

There have been several studies of the effects of contamination arising from mineral extraction and subsequent landfill, metalliferous mining for ores, process works (such as smelters and gas works), transportation transfer sites, and bulk wastes from all of the preceding activities (Parry and Bell, 1987). This leads to a general reduction in the plant carrying capacity of soils on these areas, degradation in plant communities and a concomitant decrease in groundwater quality, all of which contribute to a general decline in the biogeochemical cycling of nutrients within catchments containing such activities.

Mining operations expose extensive areas of bedrock to weathering processes, with the result that large amounts of water-soluble metal compounds contaminate drainage and groundwaters (Glover, 1975).

This can result in a significant reduction in pH and the production of the pigment ochre in surface waters. This phenomenon has been given the generic term "acid mine drainage" although some discharges are neutral and are more properly termed "ferruginous". Although there have been considerable advances in the treatment of soils likely to give rise to acid mine drainage, little attention has been given to the problem at a catchment level (Ziemkiewicz, 1990).

It is clear that many of these plot- and field-size studies have proved extremely useful in devising management regimes for the amelioration of the deleterious effects of industrial activities. However, it is equally clear that the study of the effects on a catchment scale would greatly enhance our understanding of how complete functional units respond to such stresses and disturbances. This would also enable us to be better judges of the total environmental costs of such activities allowing this to be incorporated into planning procedures.

16.7 LANDSCAPE PLANNING AND OPTIMIZATION

Agricultural catchments include, to greater or lesser extent, various non-productive semi-natural elements such as edges of fields, hedgerows, lines or islands of trees, meadows, wetlands, ponds and other small bodies of water. The natural occurrence and location of these elements depend on the topographic relief and soil structure of a catchment, but they can also be introduced or controlled by man. Ranks of trees and shrubbery typically occur throughout the catchment, while meadows, mires and bodies of water occupy mainly depressions in the landscape. The environmental role of each non-agricultural element is not the same, so their total effect helps determine a specific biogeochemical structure in a catchment (Snytka *et al.*, 1988). The elements have complex connections with larger features such as forests, lakes and rivers and increase the ecological diversity of landscape organization in general. It should be stressed that size, type and positioning of these elements are important considerations of regional landscape planning, in part because the spatial relations between them and non-point (arable fields) and point (farms of animals) sources of agricultural pollution play a significant biogeochemical role.

The ranks and clumps of trees and brush, hedgerows and forest islands decrease air erosion, scavenge particles transported by wind and also increase the humidity of the area (Caborn, 1976). They also help to stabilize the groundwater table and the volume of runoff. The biogeochemical role of these elements is not limited to abiotic factors. For example, the biological transport of nutrients by insects, birds and mammals is determined by their movement within the landscape, which relates directly to the occurrence and placement of these elements (Lewis, 1969; Wegner and Merriam, 1979).

Attention should be paid to the significance of edges of fields, borders of roads and their associated natural non-wood vegetation (herbs, etc.). Plants play a retention role for nutrients transported from fields and also increase the ecological diversity of the area. The question of the ecologically optimal size and shape of a single field is strictly connected with the biogeochemical effects of the borders.

Watercourses draining catchments in lowland landscapes are typically accompanied by flood terraces with meadows and riparian (bank) vegetation cover. These elements trap nutrients flowing from fields by surface or groundwater (Peterjohn and Correll, 1984). It has been shown to be useful to construct small retention reservoirs along the watercourses in order to lower nutrient loss from agricultural catchments. In the Kakioka Basin, Japan, elemental concentrations in agricultural runoff indicated high levels of ammonium and low levels of nitrate (Hirose and Kuramoto, 1981); this is the reverse of normal discharge patterns, but the reductive effects of the numerous rice paddies prevalent along the watercourses may account for this. The use of grasslands close to nitrogen-rich rivers for denitrification purposes and nitrate uptake after flooding of the surroundings is a technique being discussed and tested in South Sweden (U. Emanuelsson, Dept of Plant Ecology, University of Lund, Lund, Sweden, personal

communication). There are many agricultural catchments in lowland landscapes including small mires or ponds. In NE Poland, notably different nutrient concentrations were observed at outflows in comparison between a homogeneous agricultural catchment and mixed-composition catchments including mire. Differences in total N indicate that about 70% of total N flux (almost all the nitrate and half the ammonium) is trapped in mires. Also, differences in sulphate flux point to a tendency towards lower outflow in mire catchments ([Table 16.1](#)). This sink effect is due mainly to retention in biomass, microbiological immobilization and losses to atmosphere. The positive biogeochemical effects of mires in catchments can be damaged by drainage (Kruk, 1990).

Accumulation of nutrients in the lowest parts of catchments is usually accompanied by eutrophication of surface waters and enlarged growth of aquatic plants (V. Eriksson and M. Timofejeva, Estonian Land-Reclamation Project, Tallinn, Estonia, personal communication). They found that the growth of aquatic vegetation increases the roughness coefficient of the bed and retards rates of water flow and, consequently, the water level increases. For an overgrown channel, the water level may increase more than 1 metre. Aquatic vegetation may absorb a relatively large quantity of nutrients from retained surface waters. At a density of >80 plants m⁻² and biomass of approximately 3 kg m⁻² the reed *Phragmites australis* can account for an uptake of 45 g nitrates, 18 g phosphates, 22 g K and 33 g Cl during the vegetation period; at a density of >45 plants m⁻² and biomass of 3.6 kg m⁻², *Typha* sp. may accumulate 38 g nitrates, 32 g phosphates, 50 g K and 75 g Cl

Table 16.1 Effect of mires on the outflow of nutrients from two mixed agricultural-mire catchments (I and II). The figures (kg ha⁻¹ year⁻¹) represent differences from agricultural outflows minus the net outflows after passing the mires. The: percentage figures are calculated as percentages of the outflow from the agricultural areas, thus indicating the degree of mire retention (from Kruk, 1990)

Catchment	NH ₄ ⁺ -N	NO ₃ ⁻ -N	DTN ^a	SO ₄ ²⁻ -S
I	0.4 (46%)	4.5 (95%)	5.6 (71%)	5.1 (18%)
II	0.7 (52%)	1.8 (98%)	2.9 (71%)	6.6 (49%)

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^aDTN, dissolved total nitrogen, e.g. sum of ammonium, nitrate and organic nitrogen.

(Männik and Eriksson, 1988, 1989). Therefore, eutrophication may lead not only to negative consequences, but also to processes of self-purification in small catchments (V. Eriksson and M. Timofejeva, Estonian Land-Reclamation Project, Tallinn, Estonia, personal communication).

16.8 SUMMARY

The synthesis of ecological and agricultural research is of great potential importance, not least to the disciplines themselves. Ecologists can fruitfully explore the structure and function of highly disturbed natural systems with fewer, minimized components and simplified, manipulable interrelations (see Harper, 1982). Agronomists can exploit new tools and ideas for management practices which naturalize artificial agroindustrial systems and reintegrate them into the landscape in order to meet their goals of

better crops at reduced cost. Creating a more ecologically consistent agriculture, which is economically and socially sensible, will require the expertise of both fields. A comparison of conventional and "organic" farms of similar size and location sharing the same cultural and economic infrastructure (Lockeretz *et al.*, 1981) suggests that something between the two, an intermediate, hybridized farm, may offer the most viable alternative for large-scale agriculture in the immediate future.

Natural and planned differentiation of agriculturally dominated catchments play significant roles in:

1. stabilization of biogeochemical cycles;
2. retention of dissolved substances including nutrients;
3. lowering erosion and weathering effects;
4. increasing interbiocenotic biological transport.

Landscape management practices which stimulate denitrification and nitrogen uptake in runoff waters usually improve the quality of water available for human use. On the other hand, denitrification produces gases which may contribute to the "greenhouse effect", so it seems that better timing and/or reduction in application of nitrogenous fertilizers would be beneficial in the long term.

Securing shelter, food and water from the environment are the most basic and necessary of human activities; historically, practices which recycled materials and rejuvenated the land were considered so important that they acquired a "metaphysical" quality. Integrated catchment studies of natural and manipulated areas may well represent the best method for exploring human relations with the rural landscape.

Future investigations of agricultural catchments and biogeochemical effect on landscape differentiation should more widely include input-output modelling, manipulation experiments and biogeochemical mapping.

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