APPLIED ASPECTS OF INLAND AQUATIC ECOSYSTEMS

Contents

Agriculture

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Introduction

Agriculture accounts for about three-fourths of human use of fresh water and demand will increase with growth in world population. Around 40% of land surface on the planet has been converted to cropland and pastures, which nearly matches current forest cover. Intensified agriculture for humans and livestock relies on maximizing crop production by using nitrogen and phosphorus fertilizers to overcome nutrient constraints on cultivated plants (**Figure 1**). Fertilizers are often applied in excess of minimal crop needs in anticipation of higher than average yields when climatic conditions are favorable during the growing season. This practice has been cost-effective – historically fertilizers have been economical and the value of additional produce has greatly outweighed the extra cost of nutrient application.

Global fertilizer use has increased by 8-fold for nitrogen and 3-fold for phosphorus over the past four decades with measurable increases in crop production. Fertilizer use has highly increased in developing countries to achieve self-sufficiency in food production. Aerial application rates are greatest in parts of China and India but are generally higher in Europe than the United States. Commercial nitrogen fertilizer is produced by an industrial process that converts atmospheric nitrogen to available forms. This product is the largest human-generated contribution to the global nitrogen cycle. Phosphorus is mined from rich mineral deposits, converted to water-soluble forms, and distributed on arable land to increase production. Occasionally, less than half of these nutrient amendments are incorporated into harvested produce with the remainder being stored in soils or leached to surface/groundwater, or in the case of nitrogen – released as gas back to the atmosphere. Nutrient losses from intensified agriculture occur, in part, because fertilizer applications are not always synchronized with periods of peak plant growth or to avoid runoff episodes.

Intensification and specialization in agriculture has resulted in replacement of pasture-based livestock practices by large, confined animal operations. Livestock consolidation results in the transport of crop nutrients from grain- to animal-producing areas, resulting in regional imbalances in nutrient inputs and outputs with surpluses near animal operations. Historically, animal manures were used on the farm but with livestock intensification the large generation of wastes presents a regional disposal problem. Less than a third of the grain produced in North America is currently fed on farms where it is grown. Increasingly

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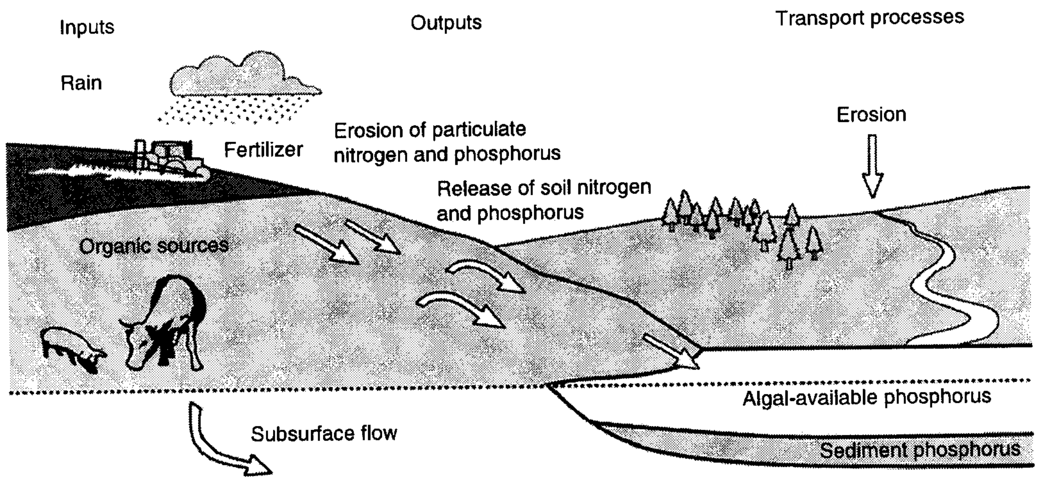

Figure 1 Idealized diagram of nutrient inputs, outputs and transport processes in an agricultural watershed Redrawn from Carpenter *et al.* (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8: 559–568.

this redistribution of nutrients is crossing geo-political boundaries on a global scale. Overall, fertilizer and manure amendments dominate nutrient cycles in agricultural watersheds and substantial losses result in nonpoint pollution, which directly impairs the water quality of surface and groundwater (**Figure 1**). Nitrogen and phosphorus stimulate plant production in streams and lakes much like the terrestrial process. Water quality problems stem from the fact that even minor losses of the total on-farm nutrient budget can cause quantifiable, negative impacts on aquatic ecosystems. Over-enrichment by nutrients (eutrophication) results in algal blooms, oxygen depletion, changes within biotic communities, and reduced utility of the water for most human uses and ecosystem services. These impacts are measurable locally but also in major river drainages, estuaries, and coastal marine areas as a result of cumulative effects.

Table 1 Export coefficients (kg ha^{-1} $year^{-1}$) from various agricultural practices

Pollutant budget estimation form

Land use	*Nitrogen export coefficient (kg ha^{-1} $year^{-1}$)*	*Phosphorous export coefficient (kg ha^{-1} $year^{-1}$)*
Forest	1.8	0.11
Corn	11.1	2.0
Cotton	10.0	4.3
Soybeans	12.5	4.6
Small grain	5.3	1.5
Pasture	3.1	0.1
Feedlot dairy	2900	220

Values from Reckhow KH, Beaulac MN, and Simpson JT (1980) Modeling phosphorous loading and lake response under uncertainty: A manual and compilation of export coefficients. Washington, DC: U.S. Environmental Protection Agency. USEPA 440/5-80-011.

Nutrient Loss and Fertilization Practices

Nutrient loss from cultivated watersheds that are fertilized is much larger than from forests and grasslands. In agricultural areas, nutrient export varies with vegetation cover, nutrient management, and related agronomic practices, terrain, soil composition, rainfall, and flow paths (hydraulic connections to surface flow), and the extent of buffer vegetation (to take up or trap nutrients). Widely cited export coefficients (Table 1) suggest N losses from corn are similar to soybeans, about 3.5-times pastures and about 6-times losses from forested catchments. For P export, losses from corn are about half that found from soybeans and about 20-times that from forest or pasture.

Applications of nitrogen (N) and phosphorus (P) to cropland accumulate in agricultural soils and are subsequently lost to surface and groundwaters by leaching and erosion. N and P have different chemistry and flow pathways. Overall, N is more likely to be transported in runoff than P because of greater mobility of its dissolved forms in water. Estimates are that 20% of N fertilizers leach into surface and groundwaters. Subsurface loss of N is as the mobile form nitrate and agricultural tile drains accelerate export. The magnitude of volatilized gaseous forms of N from agriculture (from fertilizers and manure) in the United States matches that of nitrate leaching. Most N emissions are redeposited nearby and can enter waterways.

When long term inputs of commercial fertilizer or animal manures exceed the off-take of P in harvested crops, P accumulates in agricultural soils. Inputs of fertilizer P can be greater than double the amount removed as crops causing surplus soil accumulations from an agronomic standpoint. This is common in fields near dairy barns and in one agricultural area >75% of the soils have excess phosphorus. This imbalance increases potential throughput to aquatic ecosystems that could be maintained for decades. Most soil-bound P lost from agricultural watersheds comes in overland flow from hydrologically active source areas during large erosion-causing storms. Losses are mostly particulate P (60–90% sediment and organic-bound), which may not be immediately available for biological uptake and it is the smaller dissolved fraction that is biologically available and can directly impact aquatic ecosystems. Dissolved P dominates runoff from intensive grassland areas, where erosion is modest. Loss of available P in surface runoff is closely correlated with the P content of surface soil, which increases with surplus application. P concentrations can be reduced in water that infiltrates and travels as subsurface flow from agricultural watersheds because of fixation in subsoils. Subsurface losses are regionally important in areas with sandy, well drained soils that lack capacity to retain dissolved P. Losses of P are typically <5% of the soil amendment; these losses considered minor and economically unimportant to farm production but contribute directly to water quality problems. The ultimate sink for this P is the sediments of streams, lakes, and coastal areas.

In developed countries, about 70% of harvested crops are fed to livestock and the resultant manure is comparable to human sewage, but with less stringent regulation. Intensification of the animal industry has resulted in fewer operations supplying a larger share of overall livestock production. In many cases wastes produced from single confined animal operation (housing hogs or poultry) equals the discharge of a medium sized municipality. The economic efficiency of clustering confined feeding operations in rural areas can result in waste output from intensified livestock regions to equal that of major cities. Like human sewage, animal wastes are rich in organics (high biochemical oxygen demand) and nutrients. Animal wastes from confinement operations are held or partly treated in holding ponds, collection yards, lagoons (dairy and swine facilities), or in litter (poultry operations). During storage, the N content of manure is reduced by volatilization of ammonium and other gases that contribute to the flux of N that can enter surface waters. These materials represent valuable organic matter and nutrient amendments for cultivated fields and pastures but are bulky to move and apply (solids, slurries, or liquids) when compared with commercial fertilizers. Also, there is competition for land suitable for manure application near confined animal operations. Increasingly, manure applications exceed potential crop uptake in these areas increasing the potential for loss to surface waters. Heavy metals, added to feed as micronutrients or bactericides (particularly zinc, arsenic, and copper), can also accumulate in soils. Animal wastes can also enter waterways directly from leakage or overflow of lagoons, and spills have caused fish kills in response to high ammonium ($>2\ mg\ l^{-1}$) and decreased oxygen.

Ethanol production is projected to increase maize production in North America by about 20%. Intensified crop production and conversion of idle, marginal land into crop production will potentially impact water quality. This is especially serious because much of the idle land is near to waterways and has high slopes and erodible soils. Marked expansion of ethanol production in grain-based biorefineries will also add to regional nutrient imbalances. Distillers grains generated by the production of ethanol are rich in P and protein and are typically used as a feedstock for livestock. Increased use of distiller's grains in feed can increase nutrient content of animal manure particularly on beef and dairy operations.

Manure application is typically aimed at meeting N requirements of crops, which results in a buildup of soil P. Distribution of manure to satisfy crops' P requirements requires vast amounts of land for application because, relative to crop needs, P is higher than N in manure. A United States study concluded livestock waste was the largest source of P contamination in streams and rivers. Manure amendments reduce the ratio of N-to-P in agricultural runoff, which favors cycanobacteria and increases the likelihood of algal toxin production.

Livestock wastes are a source of coliform bacteria (including the toxin producing O157:H7 strain) and protozoan pathogens (such as *Crypotsporidium* and *Giardia*) to surface and groundwaters; disease outbreaks from contaminated municipal water supplies have occurred as a result. Veterinary and nutritional pharmaceuticals, and excreted hormones from livestock enter waterways but there is a lack of information on the widespread impact of these potential pollutants on aquatic communities. About one-third of United States antibiotic use is added to animal feed to prevent infection and promote rapid growth. This practice likely contributes to the increased antibiotic resistance of microbial populations in surface water exposed to livestock wastes. Some of these chemicals affect reproductive endocrine function of wild fishes by mimicking natural hormones.

Nutrients and Sediments in Agricultural Landscapes

Lakes in agricultural landscapes may have naturally greater fertility than lakes in other biomes because of their location in arable soils that have sufficient natural fertility to generate economically viable produce. The inherent tie between soil fertility and lake productivity has been long recognized by ecologists and is nicely demonstrated in the state of Minnesota (USA). Lakes least impacted by human disturbance (reference lakes) in the agricultural plains in southern Minnesota have an order of magnitude larger P values and 5-times the N content of those in the predominately forested northern region. Lakes are intermediate in the central part of Minnesota where land cover is a mosaic of agriculture and forest. Fertilizers and manure amendments in cultivated landscapes increase nutrient export to aquatic ecosystems above background levels and are considered the major water quality impairment.

Data from a suite of Missouri (USA) streams demonstrate how N and P concentrations increase in response to crop cover, a surrogate for nonpoint source nutrient loss from agriculture (**Table 1**), and decrease with forest cover (**Figure 2**). This cross-system pattern is consistent with differences in export coefficients from these two land cover types (**Table 1**) and shows how stream water quality integrates land cover. In Iowa (USA), a region of intensive agricultural production, stream nitrate concentrations increase with watershed density of animal units and row crop and accounted for 85% of the among-stream variation in this nutrient in one study. In the Mississippi River nitrate levels have shown a 2.5-fold increase since 1960 and use of commercial N fertilizers accounts for much of this increase (**Figure 3**). Estimates suggest a <15% reduction in fertilizer use would achieve a >30% reduction in riverine nitrate flux with little influence on crop yields.

A strong cross-system pattern between nutrients in Missouri and Iowa reservoirs and cropland demonstrates how lake and reservoir fertility increases directly with agricultural cultivation in the United States mid-continent (**Figure 4**). The increase, which amounts to a 4-fold increase in P and 3-fold increase in N, reflects the increase in cropland agriculture along this geographic axis. Stream nutrients would double or triple across this continuum of increasing crop cultivation. N and P concentrations in lakes receiving run-off from agricultural watersheds in the state of Iowa have some of the highest nutrient concentrations in the world (**Figure 5**). Historical trends in agriculture and water quality in Clear Lake, Iowa (USA) shows the cumulative influence of agriculture on lake water clarity due to land clearing, draining wetlands, and intensification in an individual lake-watershed system (**Figure 6**). Collectively, these studies show extensive nutrient loss from cultivated agricultural land to stream and rivers.

Cultivation increases soil erosion and the total suspended solids load of the Missouri streams show this landscape level disturbance with direct increases with crop cover and decreases with forest (**Figure 2**). Factors that increase erosion and surplus nutrients in soil, as occurs in modern agriculture, increase the potential for nutrient loss to streams. There are no global figures but soil erosion from agriculture is considered responsible for a great deal of the sediment supplied to rivers, lakes estuaries and the oceans. In many agricultural regions of the United States, sediment is considered the greatest water quality problem. Agriculture has modified vegetation structure, riparian areas and hydrological regimes of landscapes which has increased overland flow, stream discharge and bank erosion. Maximum erosion occurs in storm events during planting and after harvest when crop cover is minimal. Soil loss leads to increased turbidity in receiving waters and light-limitation of photosynthesis. It also causes physical destruction of habitat; deposited sediment disrupts channel hydrology, blankets and intrudes into gravel beds used for fish spawning and by invertebrates, and accelerates the loss of volume in lakes and reservoirs. The clay and silt fraction is a carrier of adsorbed P, pesticides and metals. Conservation tillage, which maintains crop residues, is known to reduce runoff and soil loss.

Coastal Waters and Aquaculture

Nutrients released into lakes and rivers flow downstream leading to coastal eutrophication. Widespread eutrophication of estuaries and coastal areas by nutrient pollution, partly from agriculture, is well documented and expected to increase. In contrast to temperate lakes, eutrophication of coastal waters is frequently controlled by N. The primary symptoms of anthropogenic N enrichment of coastal areas are similar to lakes – increased, and maintained, algal production and reduced transparency. Sustained surface productivity results in greater flux of organic material to bottom sediments where bacteria consume oxygen. Oxygen cannot be renewed from surface waters because of strong stratification during summer (differences in temperature and salinity between surface and bottom layers prevent mixing) and light limitation prevents deep-water photosynthesis. Oxygen consumption results in hypoxia ($<2\,\mathrm{mg\,l^{-1}}$ oxygen) that influences

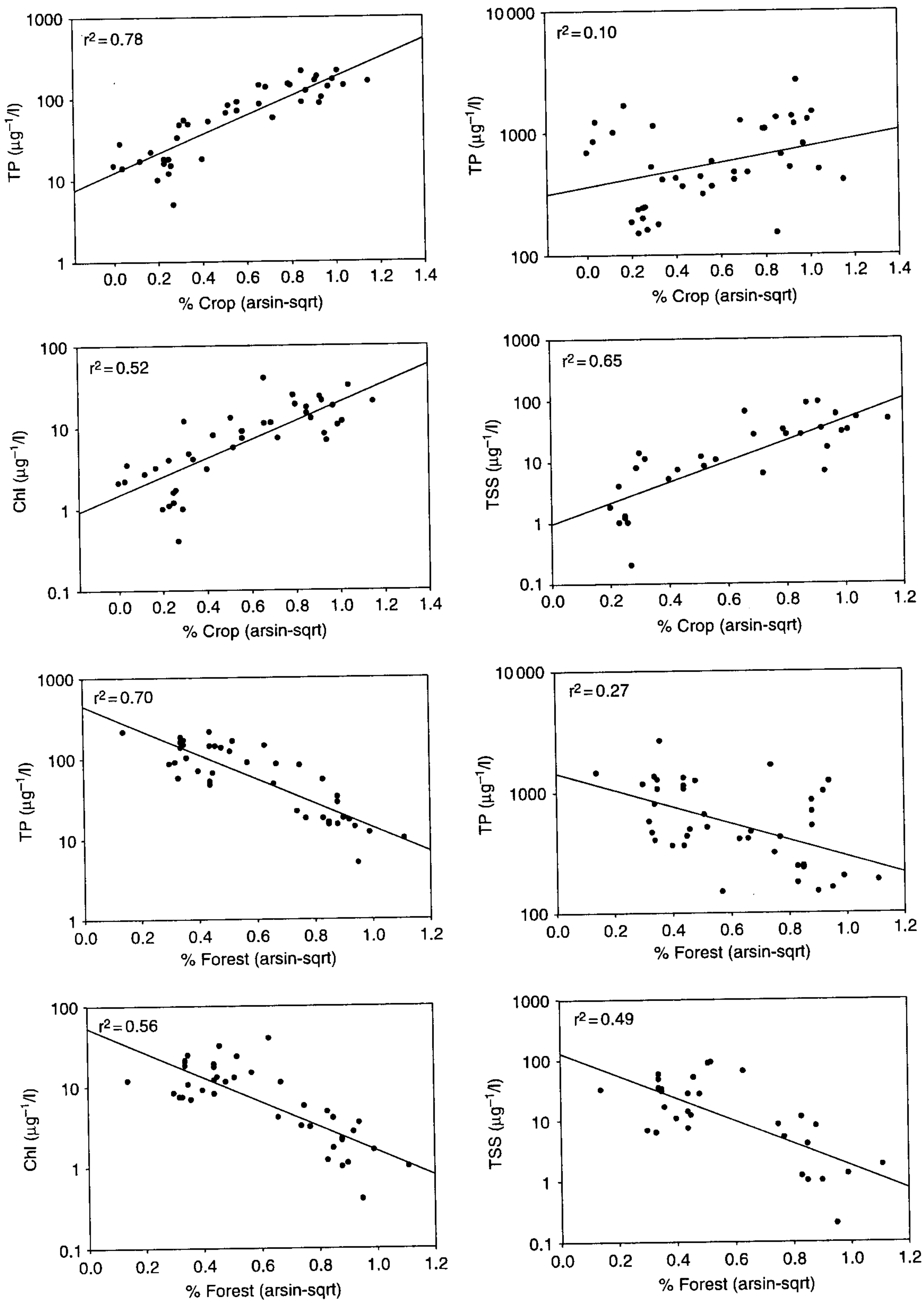

Figure 2 Values of total phosphorus (TP), total nitrogen (TN), algal chlorophyll (Chl) and total suspended solids (TSS) from Missouri Streams (log transformed) plotted against the proportion of crop (upper four panels) and forest (lower four panels) in the watershed (arcsin square root transformed). From Perkins *et al.* (1998) *Verh Internat Verein Limnol* 26: 940–947, with permission.

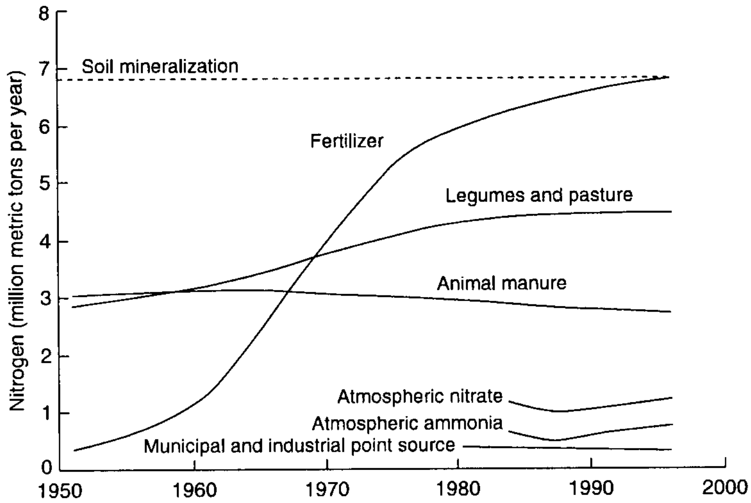

Figure 3 Historic increase in nitrogen in the Mississippi River relative to other sources. Adapted from **Figure 5** in Goolsby and Battaglin (2000) USGS Fact Sheet 135–00.

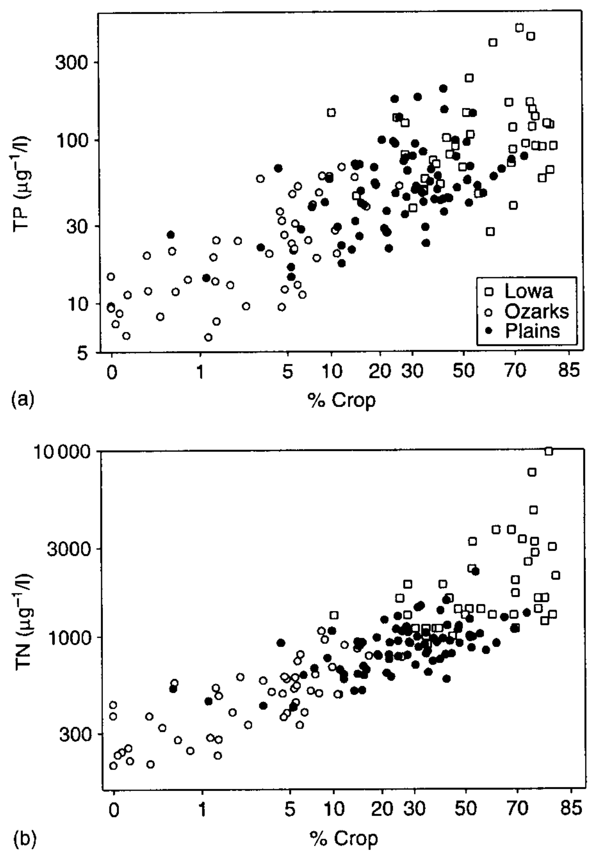

Figure 4 Relation of total phosphorus (TP, log-transformed) and total nitrogen (TN, log-transformed) in reservoirs in the Missouri Ozarks, Missouri Plains and southern Iowa to crop (logit-transformed) in the catchment of each impoundment. Figure from Jones *et al.* (2008) *Lake Reserve Management* 24: 1–9, with permission.

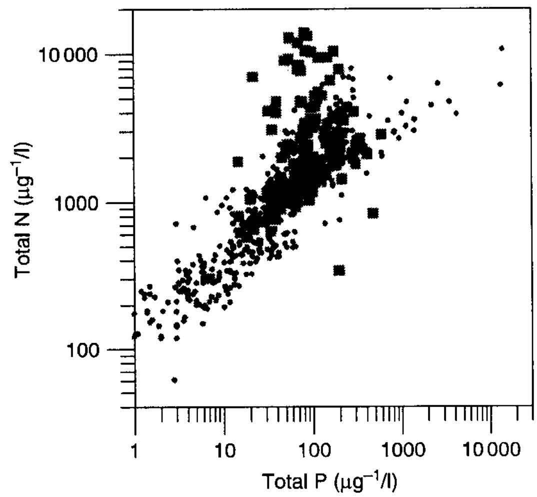

Figure 5 Average nutrient conditions in 172 lakes in a highly agricultural region (Iowa, USA from 2001–2006; red squares) plotted against average conditions in world lakes. Adapted from Downing and McCauley (1992) *Limnology and Oceanography* 37: 936–945. Only a few of the most phosphorus-rich African lakes exceed nutrient levels seen in lakes in agricultural regions.

sediment chemistry and the native biota. The condition became more prevalent worldwide in the 1960s as the ability to assimilate additional anthropogenic nutrients from urban and agricultural sources was exceeded and is now common in major bays and estuaries worldwide. Conditions are typically worse near the terminus of major rivers with altered nutrient flux and water quality.

In response to increased loads of inorganic N from the Mississippi drainage (**Figure 3**) hypoxic bottom

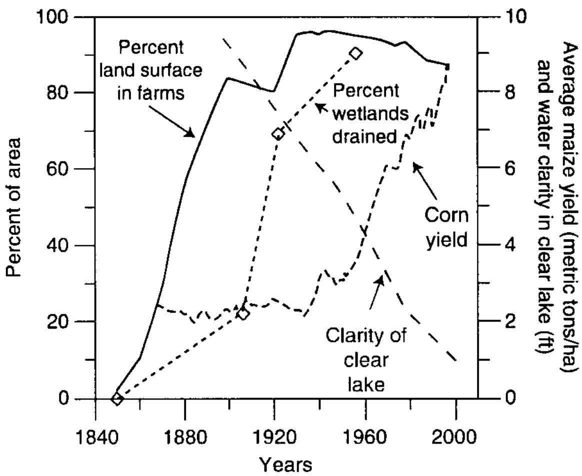

Figure 6 The lines show how the landscape of an intensively agricultural area has been altered by human activities over the last 150 years. This has been achieved by conversion of more than 90% of the land to farmland (1850–1930), drainage and tiling of more than 90% of the wetlands (1900–1960), and four-fold intensification of agricultural yields through fertilization, increased mechaniation and pesticide use (1940 to present). The red line shows the steady decline in the clarity of Clear Lake (shown in feet to fit scale) that has been correlated with changes in the Iowa landscape. Clarity in the late 1800s, allowed aquatic plants to grow to depths of 6 m. Today, water clarity is 0.3–1 m, depending on the weather and season. Data are from the United States Department of Agriculture, the United States Census Bureau and public water quality records.

water in the continental shelf of the Gulf of Mexico has rapidly developed into the largest hypoxic zone in the Western Hemisphere (from the Mississippi Delta to Texas coast). This zone varies annually in response to river flow, nutrient flux and sediment organics but has exceeded 15 000 km^2 most years since the early 1990s. It forms in the area of an important commercial and recreational fishery and when bottom waters are hypoxic, fishing boats do not capture shrimp or bottom dwelling fish. Most aquatic species cannot survive such low oxygen levels and in areas of recurring and severe hypoxia the sea floor community shows reduced abundance, species richness and biomass.

Eutrophication of coastal and estuarine waters creates a favorable nutrient pool for algal blooms and toxic or harmful algal species. Outbreaks along the eastern United States coast and in tributaries of Chesapeake Bay have been linked to nutrient inputs. Increased use of urea fertilizer may also increase the likelihood of dinoflagellates that grow well on this nutrient, including the toxic *Pfiesteria* spp., the phantom dinoflagellate.

Aquaculture ponds and net-pen cages are aquatic livestock operations representing a growing segment of the world food supply. These operations are another source of organic matter, nutrients and antibiotics to rivers, lakes and coastal areas. Water quality impacts of fish culture are typically localized near the aquaculture zone but large intensive operations have altered the tropic state of coastal waters and impoundments; culture operations have been banned from some water supply reservoirs. Discharges from recirculating flow systems to local streams can impact water quality. Culture also increases the risk of disease and parasites. Many aquatic species being cultured are not native to their farm sites or are selectively bred and differ genetically from native strains. Escapes can have irreversible ecological impacts. For example, cultured Asian carp have become established in the Mississippi basin and compete with native fish and in some coastal rivers farmed escapees outnumber wild salmon in spawning rivers.

Changes in Biota

Loss of nutrients and organic matter from agricultural landscapes increase available energy at the base of food web by promoting growth of algae, bacteria and invertebrates with potential impacts on native biota. Increased fertility results in greater overall production and biomass of lake fisheries which is beneficial but with over enrichment there is a concurrent reduction in species richness and community diversity. Changes in the trophic structure of fish communities in agriculturally eutrophic lakes involve a reduction in the proportion of desirable sport fish (primarily piscivores, such as bass) and concurrent increase of less desirable omnivorous fish that feed primarily in bottom sediments (benthivores, such as carp, roach, bream). Most sport fish are sight feeders and depend on clear, oxygenated water. In contrast, fish taxa responding positively to eutrophication tolerate poor water transparency and forage on sediment detritus and/or invertebrates without relying on vision. Feeding and bioturbation of sediments by benthivores increases resuspension of mineral turbidity and results in the translocation of nutrients to the water column which promotes planktonic algal growth and further reduces lake transparency. Omnivores directly compete with early life stages of sport fish by consuming zooplankton causing a shift in the size structure to small zooplankton. The feedback of this results in reduced recruitment of desired fish species and less grazing pressure on planktonic algae. The replacement of picivores by benthic omnivores has been documented in temperate and subtropical lakes located worldwide. In Iowa lakes (USA), with an algal chlorophyll range of 10–100 $\mu g\,l^{-1}$, the catch of sport fish per unit effort decreased by half with increased chlorophyll while the catch of bentivores doubled.

Dramatic alteration of landscapes to accommodate crop and pasture-based agriculture negatively alters stream habitats and biota. Removal of natural vegetation from overland flow pathways and along stream margins alters stream processes. Leaf and organic litter from terrestrial vegetation is an energy subsidy to the natural assemblage of stream organisms. Woody debris provides habitats and shelter for species and so promotes diversity in physical characteristics and biota of the stream channel. Riparian vegetation provides shade, moderates stream temperatures, moderates extremes in streamflow (highs and lows) and reduces diffuse loss of nutrients and sediment from agricultural watersheds. Vegetation removal opens the stream channel to direct sunlight which favors primary production (algal); this is a shift the energy base can cause functional changes in the invertebrate and fish communities that extend downstream. Species richness and composition of stream fish assemblages and overall habit quality declined in a Midwestern watershed (USA) with the extent of agriculture and increased with wetland and forest cover. These ecological processes in streams are well understood but predicting a site-specific or threshold response to nutrient enrichment is complicated by physical and biological interactions. This lack of understanding makes it difficult to quantify the benefits of nutrient management in stream ecosystems.

Pesticides

Pesticides, including insecticides, herbicides, fungicides, and vermicides are used to control insects, undesirable vegetation, microbes, and parasites that can damage plant and animal products in a variety of agricultural, silvicultural, animal husbandry, and domestic activities. Pesticide formulations have changed dramatically over the past four decades to reduce environmental persistence, bioaccumulation and nontarget toxicity. Early organochlorine insecticides such as DDT were highly toxic to nontarget organisms and bioaccumulated in food chains. These chemicals were linked to developmental and reproductive problems in wildlife and massive pesticide-related fish kills. As a consequence, they were restricted for use in many countries in the 1970s, but are still widely detected in environmental samples. Application of legacy organochlorine insecticides continues in some developing nations. In North America, Europe and elsewhere they have been largely replaced by less persistent compounds such as organophosphates, carbamates, and pyrethroids which do not bio-accumulate. Currently, some organophosphates are being removed from agricultural applications due to high neurotoxicity to birds and mammals. Herbicides account for about half of pesticide use in many areas. Most herbicides exhibit low toxicity to fish and invertebrates; however, some (e.g., atrazine) are extremely water soluble and persistent which has resulted in exceedences of human drinking water criteria. Herbicide loss to surface and groundwater can be minimized by prescription management plans which consider soil type, climate, and tillage practices. Pesticide exposure of aquatic organisms is greatest in regions of multi-crop production where irrigation water is discharged to surface waters; nevertheless, nontarget environmental impacts of pesticides have been reduced in many locations as a result of several decades of research and adaptive management.

Irrigation

Industrialization of agricultural systems to meet demands for grain and protein has moved production from rain-fed cultivation to irrigation. At present 40% of crop production comes from the 16% of irrigated land, and increases in production will require additional river diversions, surface impoundments, and groundwater withdrawal. Crop irrigation increases the potential for soil and water contact and can increase loss of P and other chemicals in return flows. Extensive irrigation withdrawal from major rivers, such as the Colorado, has greatly reduced natural flow to the sea with direct impacts on fish and wildlife. The surface areas of the Aral Sea and Lake Chad have been reduced by diversions for agriculture. Non-sustainable pumping of fossil ground water in aquifers for agriculture occurs in areas with little rainfall and inadequate surface supplies. In the Great Plains (USA), regional depletion of the Ogallala aquifer have driven irrigated agriculture out of production. Salinization is a worldwide problem resulting from irrigation; when irrigation water evaporates from the soil surface or is transpired by vegetation, salts accumulate in the root zone, causing plant stress. Millions of hectares of irrigated land on several continents are damaged by salinity and some are lost to production because of salt accumulation. Most notably in Australia salinization is occurring from ancient salts, deep in the soil profile, rising to the surface in groundwater. This is a result of land cover conversion – removal of deep rooted native vegetation and replacement by shallow rooted crop and pasture plants has reduced evapotranspiration that naturally lowered the water table. Irrigation return flows carry salts, nutrients, and pesticides from crop land to surface waters. Selenium in subsurface irrigation return flows in California (USA) have caused mortality, deformities and reproductive failures in aquatic birds in a wildlife refuge.

Remediation Measures

Blunting the adverse impact of agricultural activities on water quality is complicated because sources are nonpoint and a large number of producers contribute a small individual share to the overall problem. Most localized losses have little short-term impact on farm fertility or economy. By nature, agriculture is leaky – nonpoint pollution from farms is generated over broad areas, losses are subject to weather-related natural variability and site-specific characteristics such as topography, so measuring and controlling impacts are difficult. Regardless, some benefits can be achieved by improving farm management practices and modifying land use/cover in critical source areas where movements from soil to water are the greatest. Controlling nutrient loss from arable land begins with matching fertilizer requirements with crop needs and knowledge of nutrient reserves in soils. N application, timed to crop growth reduces potential losses by runoff and leaching. Conservation tillage increases water infiltration and reduces surface runoff and soil erosion and loss of sediment-bound chemicals, including pesticides. Seasonal cover crops provide some of these same benefits. Manure applications should be calculated to avoid surplus levels of both N and P in soils and incorporation into soil by tillage reduces the potential for losses. Matching P content of feed with the dietary requirements of animals can reduce the amount applied to land. In some locations large volume wastes generated by high-density livestock operations may need to be managed as a point source and treated as municipal wastewater to remove organic matter and nutrients to avoid surplus application to farm land. Other alternatives are pelletization or granulation for easy transport to nutrient deficient areas, composting for the landscape industry or energy generation. Healthy, deep rooted vegetation in the critical source areas where overland flow occurs within the landscape and along the margin of streams (riparian buffer zones) provide a nutrient and sediment sink and promote streambank stabilization while benefiting both wildlife and stream habitat. Wetlands in agricultural landscapes are a sink for N, which is lost as gas by microbial processes. Agriculture has at hand technical support systems that monitor nutrients and provide precision application techniques for fertilizer and pesticides to minimize nonpoint loss. Even with best management practices, however, logistical constraints, site-specific soil properties, inadequate storage facilities for animal wastes, ambient soil moisture, and storm events will influence nonpoint losses to aquatic ecosystems.

See also: Aquaculture, Freshwater; Aquatic Ecosystems and Human Health; Biogeochemistry of Trace Metals and Mettaloids; Chemical Fluxes and Dynamics in River and Stream Ecosystems; Eutrophication of Lakes and Reservoirs; Eutrophication; Lake and Reservoir Management; Phosphorus; Pollution of Aquatic Ecosystems II: Hydrocarbons, Synthetic Organics, Radionuclides, Heavy Metals, Acids, and Thermal Pollution; Pollution of Aquatic Ecosystems I; Water as a Human Resource.

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