Perspectives of Ecological Engineering to Enhance Nutrient Removal in Wetlands

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Abstract

I propose management practices which can maintain removal mechanisms of nutrients in wetlands and enhance the transformation of nutrients into valuable biological resources. In brief, characteristic biogeochemical processes of nitrogen and phosphorus under aerobic and anaerobic conditions are considered to effectively treat nutrient-enriched wastes in wetlands. Based upon diverse food chains and biomanipulation, a water quality perspective requires that wetlands be managed to function not only as a sink of nutrients but also as a source of organisms which are dispersed to adjacent terrestrial sinks of organisms. Finally, I also propose some prospective research subjects to test hypotheses related to the management practices.

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Introduction

Narrow riparian areas lying along Korean rivers and streams are very unique in terms of concentrated rainfall during a short period in summer and steep topography of surrounding catchment areas. A relatively large portion of the area experiences flooding only from early June to early September, while it is almost dry like terrestrial systems from fall to late spring. Only its small area is comparable to a wetland during the period of dry season, and allows hydrophytes to grow or lie dormant. This situations may make the Korean riverine wetlands less effective in conserving nutrients as well as water within inlands.

The unique rainfall pattern and topography are major challenges that Korea faces in managing water resources quantitatively and qualitatively. A better management, especially with the challenge, will be achieved when nutrient-enriched water is distributed to many small wetlands in a catchment rather than concentrated to one big reservoir. Otherwise, a large amount of nutrients will be washed out to river, lake, and even groundwater which are major sources of the fresh water supply in Korea, and the seas which surround the Korean peninsula. Apparently, the loss of nutrients from uplands creates depletion of valuable terrestrial resources and subsequent chronic eutrophication of the water resources.

Natural and constructed wetlands function as sink, source, or transformer of nutrients (Heath 1992, Wetzel 1992). Much emphasis has been placed on the function of nutrient sink in wetland since it is desirable from a water quality perspective. Of course, a wetland plays a significant role in removing constituents of water body during the early phase of construction. Nevertheless, the wetland will not be a permanent sink of nutrients as it becomes saturated with the nutrients.

Even when a wetland reaches a plateau of nutrient retention, however, nutrients would be sustainably removed once there is a counteracting output. As long as eutrophication of adjacent water resources is concerned, then, the air or upland is the desirable sink to receive nutrients from the wetland. Hence, many studies highlight gaseous loss of nitrogen since denitrification is a major output process through which nitogen is lost from wetland to the air (Hanson et al. 1994, Schipper et al. 1994, Lowrance 1995, Hill 1996). On the other hand, output of phosphorus is not the case since the biogeochemistry of phosphorus is not comparable with that of nitrogen. For example, there is no gaseous form of phosphorus. Inorganic phosphorus is also much less mobile than nitrate.

Hence, an adjacent upland area is considered as the alternative sink to tap nutrients from wetlands. Then, there should be any processes to lift materials up against gravity, which requires energy. From a perspective of ecological engineering, major source of the energy will not be fossil fuel. Rather, faunal processes related to locomotion and food chain are would-be energy sources or factors governing nutrient retention.

In this paper, I examine nutrient removal mechanisms in wetlands, suggest management practices which maintain the mechanisms and enhance transformation of the nutrients into valuable biological resources, incorporating biogeochemical characteristics, diverse food chains, and principles of biomanipulation, and finally propose prospective research subjects.

Nutrient Removal Mechanisms in Wetlands

In general, suspended solids tend to be deposited in areas of rough surface. Surface of vegetative zone is relatively rough, compared to that of unvegetative waterways. It is the roughness that causes deposition of suspended organic and inorganic materials in the vegetated wetlands. Wetlands also remove pathogens of the aquatic system. Suspended pathogens are deposited, and killed or weakened by antibiotics released from the roots of hydrophytes in the riparian ecosystem.

Both microbial immobilization and plant uptake are major contributions to nutrient removal in an ecosystem. In particular, excess supply of organic carbon enlarges microbial biomass, and hence immobilization of nitrogen. For example, nitrate content and its leaching loss were significantly lowered when sawdust was added to a Korean sandy loam soil and incubated for six weeks (Lee et al. 1996). Schipper (1996, personal communication) presented data showing that microbial biomass was up to 1,000 times greater in a sawdust-added New Zealand soil than in adjacent soils, suggesting that microbial uptake of nitrogen was enhanced to keep nutritional balance when organic carbon was supplied.

Biogeochemical processes in wetlands are largely associated with anaerobic conditions, which are ubiquitous when consumption of oxygen outgoes reaeration due to active digestion of organic matter. Then, as nitrate becomes the dominant electron acceptor in biochemical reaction, denitrification occurs predominantly, producing gaseous forms of nitrogen, e. g., nitrous and nitric oxides and nitrogen gas. Hence, the process results in nitrogen removal from an adjacent aquatic system. Thus denitrification is considered one of the most significant processes in removing nitrogen in the riparian system (Hanson et al. 1994, Lowrance et al. 1995).

Due to the prevalence of denitrification in wetlands, many studies have been conducted to characterize at the landscape level a place or condition where denitrification is active. But the results are not conclusive. For example, sometimes grassed wetlands removed less N than area where deciduous trees were planted (Haycock et al. 1993), but in another case, denitrification and N removal were significantly lower in woody forests than in grassed areas (Lowrance et al. 1995). As a matter of fact, denitrification is subjected to complex interaction among hydrology, plant uptake of NO_3^-, and the movement of plant N into soil NO_3^- pools through litterfall, mineralization, and nitrification (Hanson et al. 1994), as much as it is limited by the availability of nitrate or labile carbon (Schipper et al. 1994).

Phosphorus removal in wetlands is governed by chemical, biological, and hydrological processes (Mitsch et al. 1995). Phosphorus retention in wetlands is largely attributed to sedimentation and microbial uptake (Craft and Richardson 1993, Mitsch et al. 1995).

On the other hand, prolonged flooding of wetland may cause solubilization of P into aquatic systems. In general, P tends to be released from organic matter and inorganic minerals under anaerobic condition while the transition to oxidation state results in a lower amount of soluble P. For instance, at 20°C, 95% of the total P in sludge was released as phosphate under the anaerobic condition, and only 20-30% of the total P in aerobic environment (Rydin 1996). Bacterial P uptake rates are usually lower under the anoxic condition than aerobic conditions (Kerrn-Jespersen and Henze 1993). In the aerobic environment, the poly-P bacteria use organic storage products for generating energy which is utilized for growth and P storage in a form of intracellular poly-P. Under the anaerobic condition, the poly P-bacteria obtain energy from the decomposition of intracellular poly-P, which leads to the release of P in inorganic forms (Sorm et al. 1996). Increasing dissolved inorganic P under the anaerobic condition is also ascribed to less adsorptivity of P onto a reduced form of iron compound (Fe^{2+}) than onto an oxidized one (Fe^{3+}).

Although anaerobic condition forces both organic and inorganic substrates to release P into water, a vegetative area predominantly removes a large amount of sediment-bound P over the dissolution (Lee et al. 1989). Nevertheless, any practice should be given to immobilize the dissolved P in wetlands because it is readily available for primary production, and thus causes algal bloom in aquatic ecosystems.

The mechanisms by which matter is removed in a wetland are summarized in Table 1.

Examining the mechanisms above, it is noted that nutrient removal in wetlands is largely associated with hydrological and biological state variables and processes, such as loading of nutrients, relative depth of aerobic and anaerobic soil layer,

Table 1. Removal mechanisms of aquatic constituents in riparian ecosystem

Constituent	Removal mechanisms
Suspended solids	Sedimentation/filtration
Pathogens	Sedimentation/filtration
	Natural die-off
	UV radiation
	Excretion of antibiotics from roots of macrophytes
BOD	Microbial degradation (aerobic and anaerobic)
	Sedimentation (cumulation of organic matter/sludge on the sediment surface)
Nitrogen	Ammonification followed by microbial nitrification
	Microbial immobilization and plant uptake
	Denitrification
	Ammonia volatilization
Phosphorus	Soil sorption (adsorption-precipitation reaction with aluminum, iron, calcium, and clay minerals)
	Sedimentation
	Microbial immobilization and plant uptak

Modified from Brix 1993.

frequency and period of flooding, and hydraulic residence time. Hence, it is suggested that the variables and processes should be considered to better manage riverine wetlands.

Food Chain and Biomanipulation in Wetlands

In the past, the control of nutrient pollution has focused attention on less input and more removal of nutrient itself in an aquatic system. However, the practices frequently failed to ameliorate water quality which had been already degraded due to eutrophication. Although such practices apparently contribute to removal of nutrient in water body, much nutrient was regenerated by internal supply such as the release of nutrient from sediment and mineralization of organic forms. In addition, nutrient removal might be compensated by biotic processes such as less grazing pressure and changes in algal composition in terms of size selectivity of zooplankton (Kang et al. 1996). Hence, a successful management of water quality requires the control of biotic components and their ecological interactions as well as nutrient itself.

1. Food chain

As shown in Table 2, the biomass of primary producers is transformed by consumers' processes and flows through various pathways in nature (Odum and Biever 1984). The diverse pathways are maintained by diverse organisms. For instance, herbivorous vertebrates graze on living biomass, and many invertebrates such as earthworm and loach feed on organic detritus. Many microorganisms also decompose plant residues.

Table 2. Category of plant parts fed to herbivores in wetland ecosystems.

Plant part		example of herbivore
Living tissue	vegetative part	grass carp, goat
	seed, fruit	bird
Dead tissue	organic detritus	invertebrate
		loach, catfish
Dissolved	exudate	bacteria, fungi
	nectar	bee, butterfly

Especially, a large portion of hydrophytes is subject to microbial and faunal processes, leading to detritus food chain rather than grazing food chain (Newman 1991). Microorganisms and invertebrates feed on organic detritus and are grazed by fish or other meso- and macrofauna. As a matter of fact, many insects spend a period of their life cycle in aquatic systems and consume organic carbon and nutrients at least as much as they need for metabolism and storage. Once they become adults, and emerge to surrounding terrestrial systems, they remove nutrients from the aquatic system in which they live.

In addition, beautiful flowers of plants contribute aesthetically, and attract bees and butterflies, which will carry concentrated organic matter of honey and pollen to terrestrial ecosystems. Some seeds which contain a large amount of fatty acids will also be taken by birds to the terrestrial systems.

In summary, producers directly or indirectly take nutrients up in aquatic systems, and consumers enhance the process of uptake by tapping the nutrient pool of producers' biomass. As energy and nutrients are transferred to the heterotrophic biomass through food chains, each trophic level indirectly contributes to the removal of nutrients of aquatic systems at least by conserving nutrients in biomass.

2. Biomanipulation

Biomanipulation is another potential measure to ameliorate water quality by manipulating biological components rather than nutrient itself. For example, as nuisance of eutrophication in water resources is caused by algal bloom rather than by a high level of nutrient availability itself, a lower level of algal biomass is desirable. Then, grazing pressure on algae may be enhanced by zooplankton, which in turn is active when foraging by planktivorous fish is discouraged. When a number of planktivorous fish are restricted by direct artificial removal or active predation by the upper trophic level of carnivores, the practice will be at work.

In the past, most limnologists considered one way in which material flows up through trophic levels: nutrient → phytoplankton → zooplankton → fish → predators of fish. According to this concept, the increasing availability of nutrient enhances algal growth, which stimulates the productivity of zooplankton and fish by providing food. It is the so-called bottom-up process, based upon the classical concept of food chain.

On the other hand, prey-predator interactions have effects on the growth of phytoplankton to propagate through food chains. If certain fish prefer a specific group of zooplankton to another, some of phytoplankton are subjected to less predatory pressure. Hence, the productivity of phytoplankton is influenced by whether or not there is grazing pressure by top carnivores. In fact, primary productivity depends on grazing pressure as well as nutrient availability and competition with other producers although the potential standing crop of each trophic level is largely associated with nutrient availability. For example, as planktivorous fish are a under strong pressure by predators, zooplankton become active, grow to a large body size, consumes a large amount of food, and thus can lead to less standing crop of phytoplankton (Kang et al. 1996). This mechanism is called a top-down process.

In the 1970s, biomanipulation had focused on depressing grazing pressure on zooplankton, which was achieved by controlling fish population. Introduction of fishes which would feed on phytoplankton was also taken into consideration to control primary productivity, although it might be less sophisticated. For example, grass carp was introduced to Korean lakes to remove vascular plants which grow in littoral zones of impounded waters. Since the 1980s, biomanipulation study was extended to pathways of nutrient, interactions of components in food web, paying attention to control of a top-down process in food web.

Considerations for Treatment of Nutrient-Enriched Water

Based upon specific processes of N and P under aerobic and anaerobic conditions, a conceptual system is proposed to effectively remove the nutrients from water. In the system, an anaerobic subsystem is followed by a relatively aerobic one. The first subsystem is directly linked to a wastewater source, and its outflow goes down to the following aerobic one. Presumably, the anaerobic subsystem is a sort of sealed tank where oxygen supply is restricted, alternatively an open and relatively deep pond where excess waste water is dumped, while the following one is a shallow wetland whose extensive surface is exposed to the air.

In the first subsystem, aerobic digestion of organic matter hardly occurs due to limited supply of oxygen. As anaerobic reactions are predominant, a large amount of nitrogen will be removed by ammonification and denitrification, and phosphorus will be released to water body.

In the following wetland, fish grow feeding on aquatic macrophytes. As the fishes move around, they require more energy which is generated by oxidation of organic matter. Hence, fish will contribute to reducing BOD and DO. Reduced DO will escalate diffusion of oxygen from the air to water. The diffusion is also enhanced by disturbance which occurs as movement of fish aerates water body over their respiratory consumption.

As fish feed on insect larvae such as mosquitoes, they also play a role in controlling pests and processing biomass of mosquito to a protein source for human. Once metamorphosis of mosquito larvae is biochemically or genetically prevented, via the manipulation of hormones or genes, an increasing amount of mosquito larval biomass is consumed by fish that are in turn eaten by man. Of course, the larvae grow by consuming oxygen-demanding materials in water.

Dissolved phosphorus of inflows is adsorbed onto suspended soil particles in aerobic conditions. Vegetation will contribute to the deposition of subsequently phosphorus-enriched particles by hindering water flow. In addition, adsorption onto soil in bed, microbial immobilization and root uptake are to a greater or lesser extent effective in removing dissolved phosphorus in the following wetland.

The expected processes in the system are summarized in Table 3.

Table 3. Hypothetical processes predominated in a combined anaerobic pond and aerobic wetland.

Order	Condition	Expected dominant processes
first	reduced	anaerobic transformation of organic carbon denitrification desorption of phosphate
second	oxidized	aeration by movement of fish aerobic decay of organic matter plant uptake → grazing food chain microbial uptake - microbial food chain adsorption of phosphorus onto soil mineral biological control of pest

When biomass is continously accumulated in the following wetland, however, it will eventually overflow to the surrounding areas. While a substantial amount of nutrients is transported downstream by gravity, it is solar energy and biological processes, in particular, faunal processes, that transform nutrients to any states beneficial to human beings and pump to uplands against gravity. Hence, biomanipulation would be based upon the knowledge of faunal movement and food chain for enhancing nutrient removal mechanisms in the following wetland.

Even though nutrient removal is active in a wetland, an area can not be a permanent sink of nutrients as it becomes saturated with age. However, nutrient removal can be maintained when there is a counteracting output. From a management perspective, the wetland would be regarded as a source of organisms as well as a sink of essential elements. Then, the organisms of wetland would be led to a sink or trap of organisms which exists in adjacent terrestrial systems. There is no doubt that nutrients in aquatic biomass is eventually cycled in the water unless it is harvested. Furthermore, more energy is required to harvest aquatic biomass than terrestrial one.

In practice, domestic animals such as black goats and ducks may be reared to allow periodic feeding of plants and animals in wetlands. Natural sinks which attract the organisms from wetlands would be unearthed in terrestrial systems. Presumably, there would be a movement of prey from more productive wetlands to less productive terrestrial habitats, if any (Polis and Hurd 1996). This perspective is related to landscape ecology, including exchange of materials between ecosystems via geochemical and biological processes.

In addition, the function of wetland as a nutrient sink would be promoted when the sources of organic carbon are added to the riparian system. In practice, sawdust and slashed twigs are potential candidates of organic carbon sources because they have high ratios of carbon to nutrients (e.g., Schipper 1996). Then, these materials may be called nutrient trap as they fuel microorganisms and animals to scavenge nutrients in surface and subsurface runoffs (Lee et al. 1996). Surely, the organism's source of wetlands would be filled with various organisms and overflow to adjacent terrestrial organism's sinks.

Prospective Research Subjects

Based upon this review, the following research prospectives are suggested:

1. The hypothesized effectiveness in nutrient removal of the coupled anaerobic-aerobic system should be examined.
2. Quantitative determination of biomass and nutrients which are transferred from wetland to upland through the transformation of insect larvae such as mosquito, dragonfly, and so on is proposed. The results will be included in models of nutrient cycling in wetlands. Presumably, nuisance insects contribute to the treatment of waste water by removing oxygen-consuming material and nutrients in the wetlands.
3. Biomass and nutrients which are transferred by locomotive animals from water and wetland to land should be estimated. In that case, differentiation and merging of diverse food chains will be of fundamental concern.
4. Effectiveness of biomanipulation in removing nutrients should be examined collaboratively with aquatic ecologists as the subject is a matter of interaction between aquatic and riparian systems.
5. Nutrient cycling will be conceptualized at the ecosystem level in wetlands. In particular, any missing links in food chains should be unearthed and included. Finally, the conceptual model will be further refined to better describe nutrient processes in wetlands.
6. From a landscape perspective, some management practices will be contrived and tested in terms of effectiveness of nutrient removal in wetlands. For example, domestic animals may be reared to allow periodic access to plants in wetlands. In addition, natural organism's sinks in terrestrial systems which are linked to the aquatic source would be examined.

Once we understand the processes at the levels of ecosystem and landscape, both meso- and macro-fauna would be managed to contribute to nutrient removal in wetlands. In other words, both bottom-up and top-down processes should be integrated for the maintenance of water quality at an acceptable level. Then, the knowledge will nourish the field of ecological engineering to control agricultural point and nonpoint pollution.

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References

Ahn, C.-W., S.-I. Lee, D. Lee, and J.-W. Kim. 1994. Effect of watercress (*Oenanthe javanica*), loach (*Misgurunus anguillicaudalus*), and sediment on water quality in wetland microcosms. Korean Society of Water Quality Proceeding (94.5):122-127 (in Korean).

Brix, H. 1993. Wastewater treatment in constructed wetlands: system design, removal processes, and treatment performance. pp.9-22 In: Moshiri, G.A. (ed.) Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, FL.

Craft, C.W., and C.J. Richardson. 1993. Peat accretion and N, P, and organic C accumulation in nutrient-enriched and unenriched Everglades peatlands. Ecological Applications 3:446-468.

Hanson, G.C., P.M. Groffman, and A.J. Gold. 1994. Denitrification in riparian wetlands receiving high and low groundwater nitrate inputs. J. Environ. Qual. 23:917-922.

Haycock, N.E., and G. Pinay. 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. J. Environ. Qaul. 22:273-278.

Heath, R.T. 1992. Nutrient dynamics in Great Lakes coastal wetlands: Future directions. J. Great Lakes 18:590-602.

Hill, A.R. 1996. Nitrate removal in stream riparian zones. J. Environ. Qual.

25:743-755.

Kang, S., S. Yoo, and D. Lee. 1996. Examination of compensatory response in trophic cascade with size-selective consumption model. (To be submitted to Ecological Modelling).

Kerrn-Jespersen, J.P., and M. Henze. 1993. Biological phosphorus uptake under anoxic and aerobic conditions. Wat. Res. 27:617-624.

Lee, D., T.A. Dillaha and J.H. Sherrard. 1989. Modeling phosphorus transport in grass buffer strips. Journal of Environmental Engineering 115:409-427.

Lee, H., G. Yoo, and D. Lee. 1996. Interaction of acidity and carbon source as related to microbial and biochemical properties in a sandy laom soil (manuscript).

Lowrance, R., G. Vellids, and R,K. Hubbard. 1995. Denitrification in a restored riparian forest wetland. J. Environ. Qual. 24:808-815.

Mitsch, W.J. 1993. Ecological engineering: A cooperative role with the planetary life-support systems. Environ. Sci. Technol. 27:438-445.

Mitsch, W.J. and J.G. Grosslink. 1993. Wetlands. 2nd ed. Van Nostand Rienhold, New York, NY. USA.

Mitsch, W.J., and S.E. Jorgensen. 1989. Ecological Engineering: An Introduction to ecotechnology. John Wiley & Sons, New York, NY.

Mitsch, W.J., J.K. Cronk, X, Wu, R.W. Nairn, and D.L. Hey. 1995. Phosphorus retention in constructed freshwater riparian marshes. Ecological Applications 5:830-845.

Mitsch, W.J., and R.E. Wilson. 1996. Improving the success of wetland and creation and restoration with know-how, time, and self-design. Ecological Applications 6:77-83.

Newman, R.M. 1991. Herbivory and detritivory on freshwater macrophytes by invertebrates: a review. J.N.Am. Benthol. Soc. 10:89-114.

Odum, E.P., and L.J. Biever. 1984. Resource quality, mutualism, and energy partitioning in food chains. American Naturalists 124:360-376.

Polis, G.A., and S.D. Hurd. 1996. Allochthonous input across habitats, subsized consumers, and apparent trophic cascades: Examples from the ocean-land interface. pp.275-285 In: G.A. Polis and K.O. Winemiller (eds.) Food Webs: Intergration of Patterns and Dynamics. Chapman & Hall, New York, NY.

Rydin, E. 1996. Experimental studies simulating potential phosphorus release from municipal sewage sludge deposits. Wat. Res. 30:1695-1701.

Schipper, L.A., C.G. Harfoot, P.N. McFarlane, and A.B. Cooper. 1994. Anaerobial decomposition and denitrification during plant decomposition in an organic soil. J. Environ. Qual. 23:923-928.

Schipper, L.A. 1996. Denitrification of groundwater nitrate in an artificial riparian wetland (manuscript).

Sorm, R., G. Bortone, R. Saltarelli, P. Jenicek, J. Wanner, and A. Tilche. 1996. Phosphorus uptake under anoxic conditions and fixed-film nitrification in nutrient removal activated sludge system. Wat. Res. 30:1573-1584.

Wetzel, R.G. 1992. Wetlands as metabolic gates. J. Great Lakes Res. 18:529-532.