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Stream corridor restoration research: a long and winding road

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Abstract

Stream corridor restoration research and practice is presented as an example of the application of ecology and engineering to solve a class of environmental problems. Interest and public investment in stream corridor restoration has increased sharply in developed nations over the last two decades, as evidenced by the volume of technical and refereed literature. However, real progress at the regional and national scale depends on successful research outcomes. Research addressing problems associated with stream corridor ecosystem restoration is beset by numerous problems. First, terms referring to restoration are loosely defined. Secondly, stream ecosystems are not amenable to rigorous experimental design because they are governed by a host of independent variables that are heterogeneous in time and space, they are not scalable, and their response times are often too long for human attention spans. These problems lead to poorly controlled or uncontrolled experiments with outcomes that are not reproducible. Extension of results to other sites or regions is uncertain. Social factors further complicate research and practice—riparian landowners may or may not cooperate with the experiment, and application of findings normally occurs through a process of suboptimal compromise. Economic issues, namely assigning costs for present and future ecosystem services that provide off-site benefits, further impede progress. Clearly, the situation calls for a hybrid approach between the rigor of the ecologist and the judgment and pragmatism of the engineer. This hybrid approach can be used to develop creative, low-cost approaches to address key factors limiting recovery.

Keywords: Stream corridor restoration; Ecology and engineering; Habitat; Fish; Vertebrates; Agriculture; Experiments

1. Introduction

Society today is faced with growing environmental problems, and one of the possible responses is represented by the theme of this conference—the creation of a new hybrid discipline to craft creative solutions based on the best science. In particular, a blend of physical sciences (including engineering) and life sciences is envisioned (Gore et al., 1990; Rabeni and Sowa, 1996), since understanding physical habitat requires physical approaches, while evaluating habitat is the province of the life scientist. However, is creation of a hybrid discipline truly an effective response, or simply another example of using activity as a substitute for progress? Assuming that a new discipline is needed, it must be targeted at application of science to solve problems at the watershed, landscape, or regional scale. Academic cultures tend to be slow to accept change in fundamental values; namely, rewards tend to be greatest for creation of new knowledge for its own sake rather than application of knowledge. Development of ecological engineering will require some

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reassessment of professional and institutional culture for both the ecologist and the engineer (e.g. Pringle, 1999).

2. Stream corridor restoration

Stream corridor restoration offers an example of the kinds of problems that are presented when a hybridization of applied ecology and engineering is attempted. Interest and public investment in stream corridor restoration has increased sharply in developed nations over the last two decades, as evidenced by the volume of technical and refereed literature (Fig. 1). This new activity has fostered much interdisciplinary collaboration in the research and practice arenas. Real progress in generating engineering guidance has been retarded by several factors; among them are communication problems, difficulties in measuring system status, and poorly controlled or uncontrolled experiments.

2.1. Definitions

Extensive discussions of the terms used to refer to activities that may be loosely grouped under the heading of stream restoration are provided by the National Research Council (1992), Brookes and Shields (1996), and the Federal Interagency Stream Restoration Working Group (1998), among others. A sample of definitions is provided in Table 1. Stream restoration in the strict sense is impossible, since it implies a full return to a prior structure and function. Rehabilitation, which refers to a partial return of former function, is most commonly the goal of “stream restoration” projects. Definitions are particularly important when working with several disciplines due to variations in professional culture, jargon, and paradigms. For example, accelerated erosion is one of the primary causes of stream corridor degradation, and also impacts human structures and activities in the riparian zone. Thus, from the engineering viewpoint, stream channel stabilization is a basic goal of almost all stream restoration projects. However, from an ecological viewpoint, natural levels of channel dynamism and instability provide large woody debris inputs, create habitats for pioneering plant species, form new backwaters through channel migration and meander cutoffs, and maintain bed sediment quality for gravel spawning organisms. Destabilization may be required for restoration. Herein, we use the term restoration to refer to any of the activities described in Table 1.

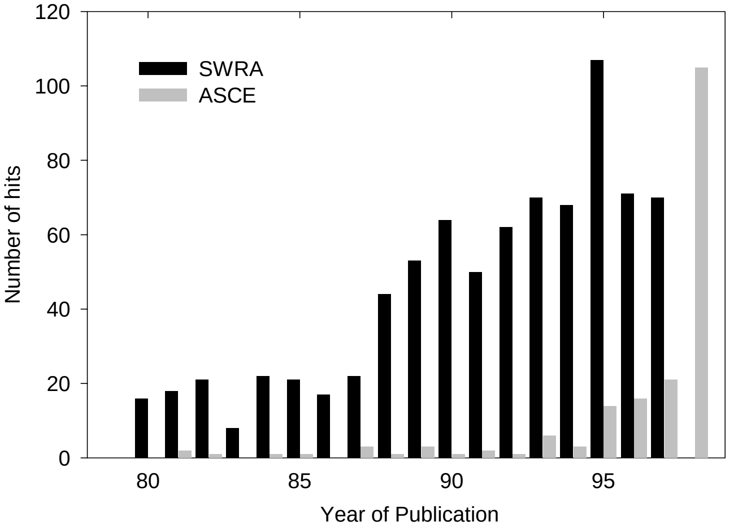


Fig. 1. Number of citations obtained from Water Resources Abstracts Database (November 1998) and ASCE website database (http://www.pubs.asce.org/cedbsrch.html, February 1998) when searched with keywords ((stream or river) and restoration) vs. publication year.

Table 1
Definitions for terms often associated with river restoration (National Research Council, 1992; Brookes and Shields, 1996; Federal Interagency Stream Restoration Working Group, 1998)

Term	Definition	References and remarks
Restoration	Reestablishment of the structure and function of ecosystems. Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. In the U.S. "predisturbance" usually refers to pre-European settlement. Since ecosystems are dynamic, perfect replication of a previous condition is impossible	The restoration process reestablishes the general structure, function, and dynamic but self-sustaining behavior of the ecosystem. It is a holistic process not achieved through the isolated manipulation of individual elements
Rehabilitation	Partial recovery of ecosystem functions and processes. Rehabilitation projects include structural measures and "assisted recovery." Assisted recovery refers to removal of a basic perturbation or disturbance (e.g. excluding grazing livestock from a riparian zone) and allowing natural processes (e.g. regrowth of vegetation, fluvial processes) to operate, leading to recovery of ecosystem function	Rehabilitation does not necessarily reestablish the predisturbance structure, but does involve establishing geological and hydrologically stable landscapes that support the natural ecosystem mosaic
Preservation	Activities to maintain current functions and characteristics of an ecosystem or to protect from future damage or losses	
Mitigation	An activity to compensate for or alleviate environmental damage. Mitigation may occur at the damaged site or elsewhere. It may involve site restoration to a socially acceptable condition, but not necessarily to a natural condition	Mitigation is often a permit requirement as part of some non-restoration type of action; it thus may form the basis for a restoration project
Naturalization	Management aimed at establishing hydraulically and morphologically varied, yet dynamically stable fluvial systems that are capable of supporting healthy, biologically diverse aquatic ecosystems. Does not require reference to a certain pre-existing state	The naturalization concept (Rhoads and Herricks, 1996; Rhoads et al., 1999) recognizes that naturalization strategies are socially determined and place-specific. In human- dominated environments recurring human management and manipulation may be a desired and even necessary ingredient in the dynamics of the "naturalized" system
Creation	Forming a new system where one did not formerly exist (e.g. constructing a wetland)	Concepts similar to those used in restoration or rehabilitation are often applied to produce ecosystems consistent with contemporary hydrology and morphology
Enhancement	Subjective term for activities undertaken to improve existing environmental quality	Stream enhancement projects of the past often emphasized changing one or two physical attributes in expectation that biological populations would respond favorably. But monitoring data were typically limited
Reclamation	A series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery	Historically used to refer to adapting wild or natural resources to serve a utilitarian purpose, e.g. draining wetlands for agriculture

Implicit in the terms in Table 1 is the ability to gage environmental degradation and recovery. Terms like ecological health or ecological integrity are often used to express judgments about ecosystem status; they are based on analogies that may or may not be appropriate (Sutter, 1993; Steedman, 1994). Since ecosystems are complex collections of physical, chemical and biological systems, much data is required to assess the status of a given system. Efficient indicators are in great demand. These may be simple, single parameter quantities thought to indirectly express ecosystem status (e.g. the number of nesting pairs of bald eagles or the percent of stream length bordered by woody vegetation), or numerical combinations of several parameters (e.g. Karr, 1993). All indicators involve considerable subjectivity in selection and weighting of parameters, and may be difficult to calibrate and interpret. For example, a popular index based on fish samples was found to poorly reflect physical habitat conditions in 27 stream reaches in northwestern

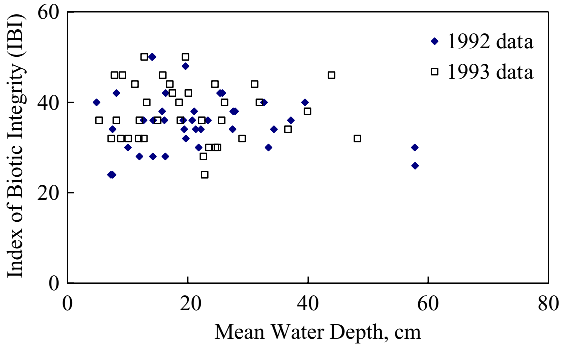


Fig. 2. Index of biotic integrity (IBI) based on fish samples collected from 37 streams in northwestern Mississippi vs. mean water depth, a key descriptor of physical habitat quality (Shields et al., 1994). Data collected and IBI computed as described by Shields et al. (1995).

Mississippi (Fig. 2), perhaps because the index was originally developed to measure conditions in Midwestern stream ecosystems suffering primarily from water quality degradation, rather than physical habitat degradation. Conversely, fish-based indicators proposed by Wichert and Rapport (1998) based on work in Ontario were significantly correlated ($P < 0.04$) with four selected descriptors of physical habitat quality in 10 reaches of two rivers (Shields et al., 2000) (Fig. 3). Transfer of research results into general guidance for practice is hindered by the absence of universally applicable indicators or control variables.

2.2. *Practice*

In general, the ecologist is concerned with modifying a degraded stream corridor to regain diversity or abundance of biological populations, while the engineer is concerned with producing systems or structures that meet certain criteria, usually those specified by the client. Accordingly, many "stream restoration projects" are essentially landscaping efforts, especially those in urban settings. Since these efforts usually do provide positive benefits in terms of downstream water quality, urban amenity, or biological resources, they

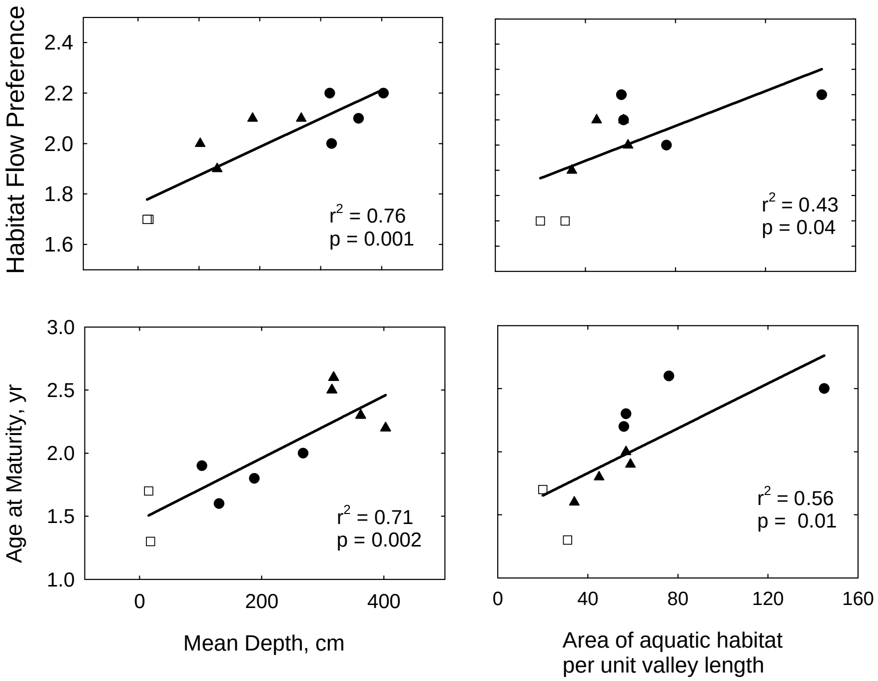


Fig. 3. Plots of fish-based ecological indicators proposed by Wichert and Rapport (1998) ("selected species association characteristic scores") for each of ten sampled river reaches in northwestern Mississippi vs. selected descriptors of physical habitat. Open squares represent reaches along a channelized river, black triangles represent reaches along a channelized river that has been blocked by sediment and debris, thus creating near-lentic conditions, and black triangles represent reaches along a naturally sinuous river. Lines are ordinary least-squares regression lines, and r^2 and P values refer to the regression (after Shields et al., 2000).

are worthwhile even though they may be misnamed from an ecological viewpoint. Although no data are available, today few channel modification projects lack environmental restoration or enhancement as a stated goal, if only for political reasons.

Stream restoration practice varies widely from region to region and between urban and rural areas. For example, large-scale projects to improve salmonid habitats are found in the Pacific Northwest, while meander restoration in small streams has been performed at several sites in England and Denmark. Beaver reintroduction, dam removal, reforestation, establishment of riparian buffer strips, and wastewater management have all been practiced and billed as stream restoration (Brookes and Shields, 1996; Federal Interagency Stream Restoration Working Group, 1998). The basis for most projects is the belief that re-creation of "natural" conditions (i.e. some status that pre-dated major cultural impacts) is good. Due to wholesale changes in watershed land use and hydrology, though, the created conditions may differ markedly from historic or prehistoric norms. Guidelines for design of channel modifications are frequently empirical, and dangerously based on data sets from other physiographic regions (e.g. Rosgen and Fittante, 1986). Most projects lack clear-cut, quantifiable, ecological objectives, and reports of success or failure are rare.

2.3. Research

A full review of stream corridor restoration research is beyond the scope of this paper and beyond our capabilities. Clearly, a scientific basis is needed for effective restoration practice. The breadth of disciplines that impinge upon stream corridor restoration is daunting for even the most devoted student of the literature. Many threads of fundamental research are relevant to restoration practice: precipitation-runoff relations, hydrologic modeling, sediment transport, erosion of cohesive materials, groundwater–surface water interactions, large woody debris functions, fish community structure, and riparian plant community succession, to name a few. Knowledge gained in fundamental areas is gradually working its way into restoration practice either directly or through applied research projects.

Here we use the expression "applied research projects" to refer to experimental restoration of a watershed or stream reach (e.g. Shields et al., 1998). Since these projects involve large-scale construction and long term monitoring, they are costly. However, yield of scientific information is limited. Since stream ecosystems are governed by a host of independent variables that are heterogeneous in time and space, they are not scalable, and their response times are often too long for human attention spans. These problems lead to poorly controlled or uncontrolled experiments with outcomes that are not reproducible. Extension of results to other sites or regions is uncertain. Experimental approaches usually involve modifying one or more physical attributes judged to be key factors limiting ecological recovery, and monitoring physical or biological response. Biotic interactions and climatic effects are usually not accounted for directly. The best approach usually includes monitoring the treated system and untreated reference systems before and after modification—a before and after, with and without design.

Even rather well-planned research can produce ambiguous results. We conducted a 5-year study of five streams (Shields et al., 1998). One-km reaches of two degraded streams were selected for restoration and were matched with similar streams nearby that were degraded, but not treated. The fifth stream was a lightly-degraded reference site. Monitoring occurred before and after habitat rehabilitation, which involved construction of stone spurs and weirs, and planting woody vegetation. Physical and biological responses of the treated streams were not proportional (Table 2). Physical response was modest in stream HC, but fish population response was dramatic, while physical conditions were transformed at GC, fish populations showed only modest improvement. However, fish species composition was transformed at both sites, with small colonists (primarily cyprinids and small centrarchids) becoming less dominant; and larger centrarchids, itcalurids, and catostomids becoming more prevalent (Fig. 4). Similar results were observed in a more modest study involving only two small streams (Shields et al., 1997). These results were rationalized using a conceptual model based on conceptual models of incised channel evolution (Simon, 1989) and warmwater stream fish communities (Schlosser, 1987) (Fig. 5). Basically, we think the treated streams differed in the strength of their biological response to physical rehabilitation because they occupied different initial states in the continuum described by the

Table 2
Response to two habitat rehabilitation experiments, northwest Mississippi, 1991–1995 (Shields et al., 1998)

	Stream HC	Stream GC
Primary treatment	Addition of stone spurs	Addition of stone weirs
Change in pool area, % of habitat	3–6	32–78
Mean number of fish species per sampling date	11–19	17–17
Mean fish biomass obtained by electroshocking 100 m	0.18–2.70	1.33–1.20
Mean number of fish obtained by electroshocking 100 m	10–16	37–12

conceptual model. However, effects of water depth on fish sampling gear efficiency, hydrologic factors, and differences in accessibility of treated reaches to source areas for colonizing organisms were all identified as possible factors in the differential response. Shortcomings of field-scale ecological experiments outlined above made exact identification of causal factors impossible. Despite the efforts directed toward long term water quality and ecosystem monitoring, long-term outcomes of ecological restoration are rarely reported (but see Short and Ryan, undated), since study duration is dictated by funding arrangements that are almost always of less than 5-year duration (Kondolf and Micheli, 1995; Kondolf, 1995; Downs and Kondolf, 2002; Bash and Ryan, 2002).

2.4. Application of research to practice

Clearly, major gains in ecological quality will require landscape-scale management approaches (Schlosser, 1991). However, such broad application of research findings is beset by social and economic problems. Landowners are often not rewarded for making investments in environmental resources that yield public benefits. When land management practices targeted at environmental goals are adopted, it is often through a process of compromise that yields suboptimal outcomes. Farmland is increasingly held in large tracts by absentee landowners that lack a long-term stewardship perspective, and view farms as investments that should yield realistic returns. Landowner decision making is complex, and adoption of conservation practices by farmers is not as amenable to prediction as adoption of other types of technology. Napier and Tucker (2001) collected data from 1011 farmers in three Midwestern watersheds in Ohio, Iowa, and Minnesota and compared frequency of use of conservation practices to 11 independent variables identified from social exchange theory. Combinations of the independent variables formed by regression analysis explained only 2–19% of the variance in conservation behaviors.

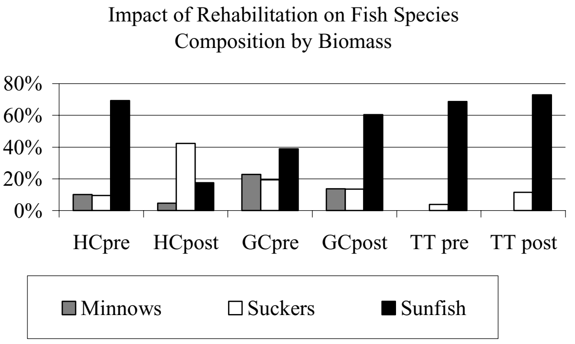


Fig. 4. Fish species composition before and after rehabilitation. Streams HC and GC were treated with stone structures and planting woody vegetation to address habitat degradation. Stream TT was a lightly-degraded reference stream concurrently sampled (after Shields et al., 2000).

3. Ecological engineering as a solution

Despite the difficulties described above, a blend of ecology and engineering has much to offer. When the engineering design process is informed by knowledge about ecological processes, substantial environmental benefits may be obtained at reduced cost. Three examples will be provided: incidental vertebrate habitat benefits provided by edge-of-field water control structures, contaminant trapping and processing in drainage ditches, and the use of structures comprised of large woody debris for controlling channel erosion. The reader will note that the first two examples are not truly ecological engineering, but are studies dealing with biota that have colonized physical structures designed and managed without ecological criteria. Intentional

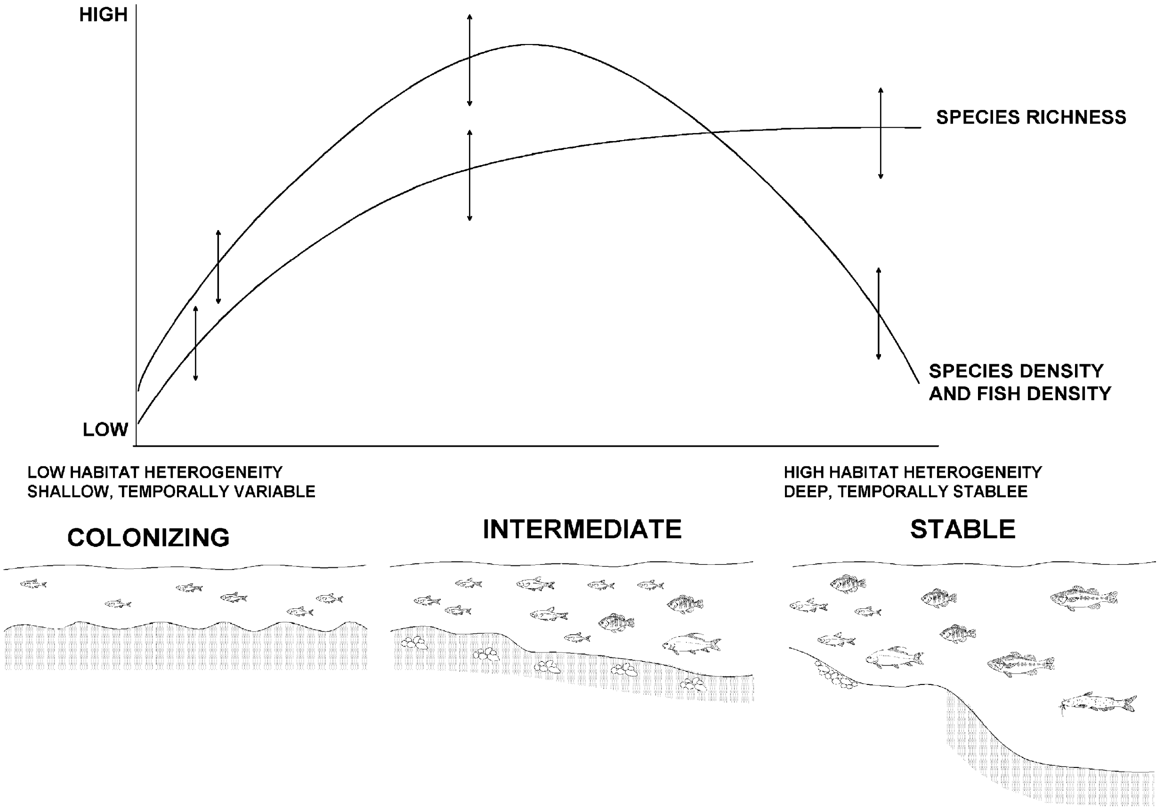


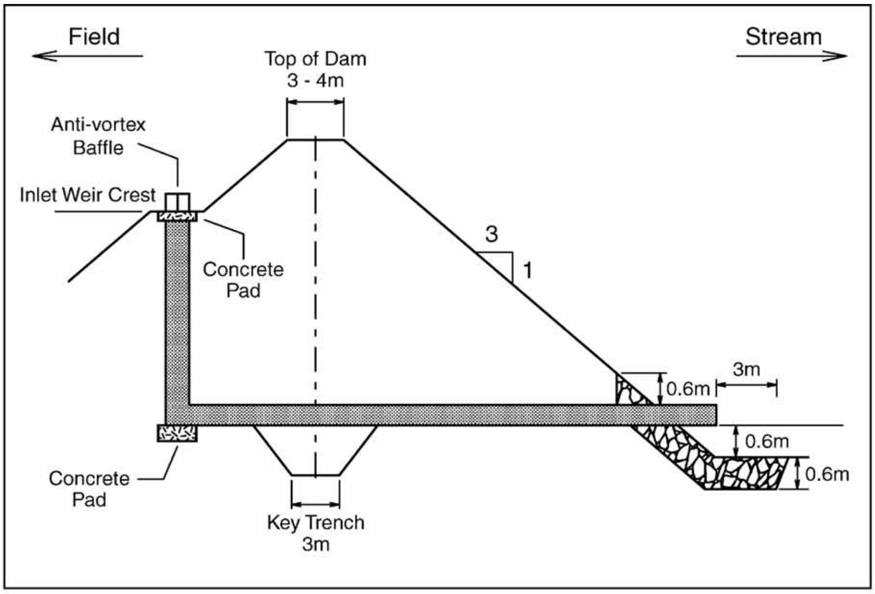
Fig. 5. A conceptual framework for fish communities in small warmwater streams (after Schlosser, 1987 and Shields et al., 1998). The adjectives colonizing, intermediate, and stable apply to the fish community, not the channel. We hypothesize that disturbance due to channel incision typically results in habitat changes and transformation of fish communities toward the left of the figure while recovery results in opposite trends.

incorporation of ecological criteria (e.g. genuine ecological engineering) might produce even more significant outcomes.

3.1. *Edge-of-field structures*

Channel incision in agricultural watersheds often triggers gully erosion at locations where overland flow crosses streambanks. Gullies may be controlled by structures comprised of earthen dams with L-shaped metal pipes provided to pass runoff through the structure and to dissipate energy without erosion (Fig. 6). These structures occur at frequent intervals in treated watersheds. For example, about 980 were installed in between 1984 and 1999 to treat riparian gullies along channels draining 16 watersheds with a total area of 6800 km^2 (Personal communication, Mr. Philip Haskins, U.S. Corps of Engineers, Vicksburg, MS). Incidental environmental benefits occur when the regions immediately adjacent to these structures are managed to allow maintenance of a small pool with natural vegetation. Sixteen drop pipe sites constructed in northwestern Mississippi were sampled for fish, amphibians, reptiles, birds, and mammals; and physical habitat characteristics were assessed by sampling vegetation and surveying site topography. These structures were designed without reference to ecological criteria. Speciose sites (those yielding 65–82 vertebrate species) were relatively large (>0.09 ha), with a significant pool area. Depauperate sites (only 11–20 species captured) were smaller, with no pool area and little woody vegetation (Fig. 7) (Shields et al., 2002).

Despite the environmental benefits provided by habitats adjacent to drop pipes, a survey of 180 drop



(a)

(b)

Fig. 6. (a) Schematic of drop pipe structure including earthen embankment, and (b) oblique air photo of recently completed drop pipe viewed from downstream (stream channel) side of the embankment.

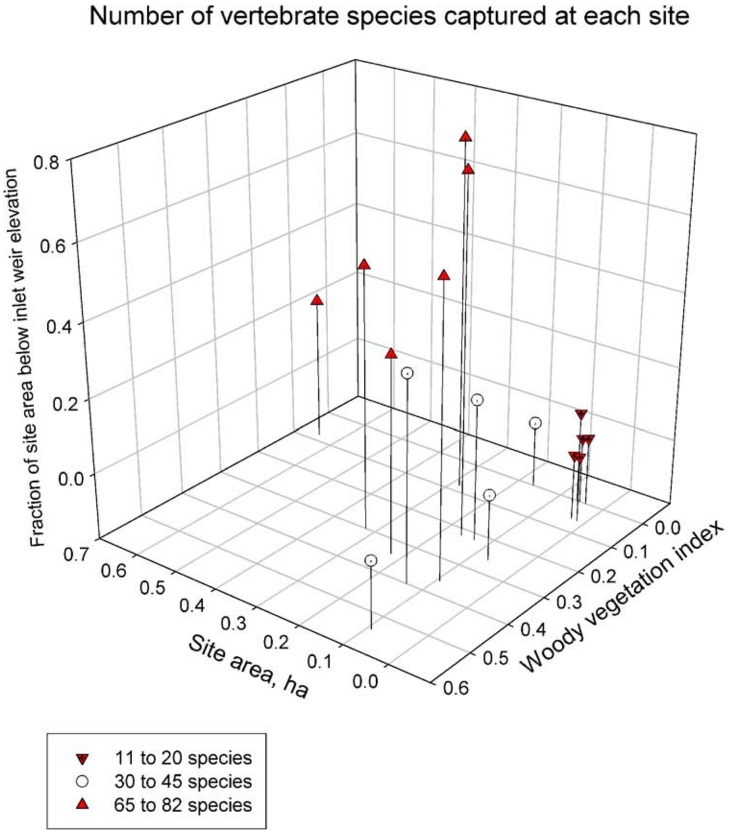


Fig. 7. Sixteen drop pipe habitats in northwestern plotted in three-dimensional space with axes corresponding to key physical habitat variables. Symbols indicate the total number of vertebrate species captured during the course of a three-year study.

pipes in Mississippi during 1994 revealed that only 7.2% of the sites provided habitat typified by pool development, vegetative structure, and relatively large area (Fig. 8a). Sites with minimal vertebrate habitat value (no permanent pool, monotypic exotic herbaceous vegetation, restricted area, Fig. 8b) were most common, comprising 61% of sites surveyed (Shields et al., 1995). Habitat conditions reflected landowner practices, site topography, and design, but intentional consideration of ecological values in design and management was not observed.

3.2. Drainage ditches

Drainage ditches are another common component of many agricultural landscapes. Ditches vary widely in size, hydrology, and in floral and faunal communities they support, but typically represent the basic unit of the stream network (“zeroth order streams”). Recent study of the fate of pesticides in ditches draining cropland in the Mississippi Delta (the alluvial plain of the lower Mississippi River) indicates that ditches may trap and retain most of the pesticides entering the ditch as runoff. Experiments designed to simulate runoff events occurring shortly after pesticide application were reported by Moore et al. (2001a and b). Study sites were managed without reference to ecological criteria. In the first experiment, a 50 m portion of a vegetated agricultural drainage ditch was dosed with a mixture of the herbicide atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) and the insecticide λ-cyhalothrin [8-cyano-3-phenoxybenzyl-3-(2-chloro-3,3,3-trifluoro-1-enyl)- 2,2-dimethyl cyclopropanecarboxylate] simulating pesticide runoff from a 10 ha field. Dominant plant species present in the ditch included *Polygonum* sp. (water smartweed)

Fig. 8. Range of habitat conditions commonly found in northwestern Mississippi drop pipe areas. (a) Large wetland with permanent pool, woody debris, and shoreline woody vegetation. (b) Small site lacking permanent pool and showing effects of periodic mowing.

Table 3
Partitioning of pesticides in agricultural drainage ditches during simulated runoff experiments

Experiment	Compound	Duration (days)	Water	Sediment	Plants
50 m ditch, simulated runoff from 2 ha	Atrazine	28	15 ± 24	28 ± 23	57 ± 21
	λ-Cyhalothrin		1 ± 1	2 ± 1	97 ± 0.4
650 m ditch, simulated runoff from 20 ha	λ-Cyhalothrin	99	1 ± 1	12 ± 16	85 ± 16
	Bifenthrin		1 ± 0.5	18 ± 28	81 ± 28

and *Leersia* sp. (cutgrass). The second experiment was conducted on a 650 m vegetated agricultural drainage ditch with a mixture of two pyrethroid insecticides, λ-cyhalothrin and bifenthrin [[2 ethyl(1,1′-biphenyl)-3-yl] methyl 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-cyclopropanecarboxylate], simulating pesticide runoff from a 20 ha field. *Ludwigia* sp. and *Lemna* sp. were the dominant aquatic flora. In both experiments, samples of water, sediment, and plant material were collected at regular spatial and temporal intervals and analyzed for the injected pesticides.

Injected pesticides were rapidly removed from the water column by sediment and plants, and remained in these components throughout the remainder of the experiment (Table 3). The concentration of λ-cyhalothrin in water declined with the square of the distance downstream from the injection point (Fig. 9). In the first experiment, 59–61% of the measured atrazine was associated with plant material during the first 24 h following initiation of the simulated storm runoff. Approximately 97% of the measured λ-cyhalothrin was associated with plant material only 3 h following the initiation of the storm event. In the second experiment, 3 h following the initiation of the simulated storm event, 96% of the measured λ-cyhalothrin was associated with aquatic plant material, while the remaining 4% was associated with the ditch sediment. Ninety-nine percent of the measured bifenthrin was associated with aquatic plant material, 3 h following initiation of the simulated storm event.

3.3. Large woody debris structures

Large woody debris is an essential component of warmwater stream ecosystems, where it may support much of the invertebrate production (Wallace and Benke, 1984), retain organic matter (Shields and Smith, 1992; Hauer, 1989), and provide essential structure, cover, and physical diversity for fish (Angermeier and Karr, 1984; Warren et al., 2002).

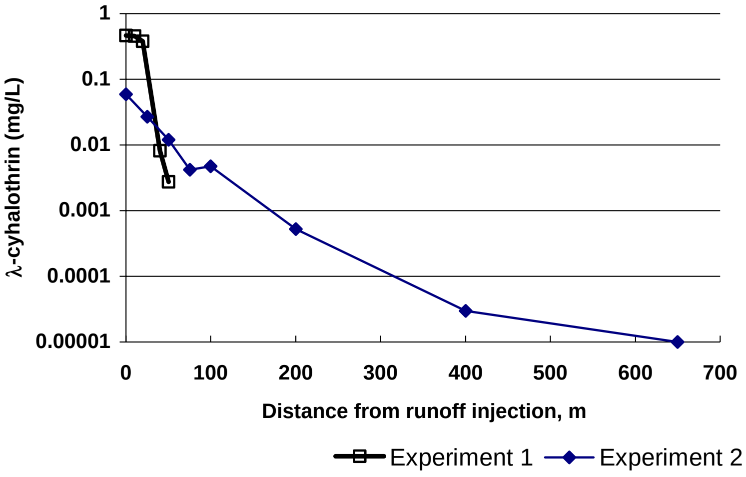
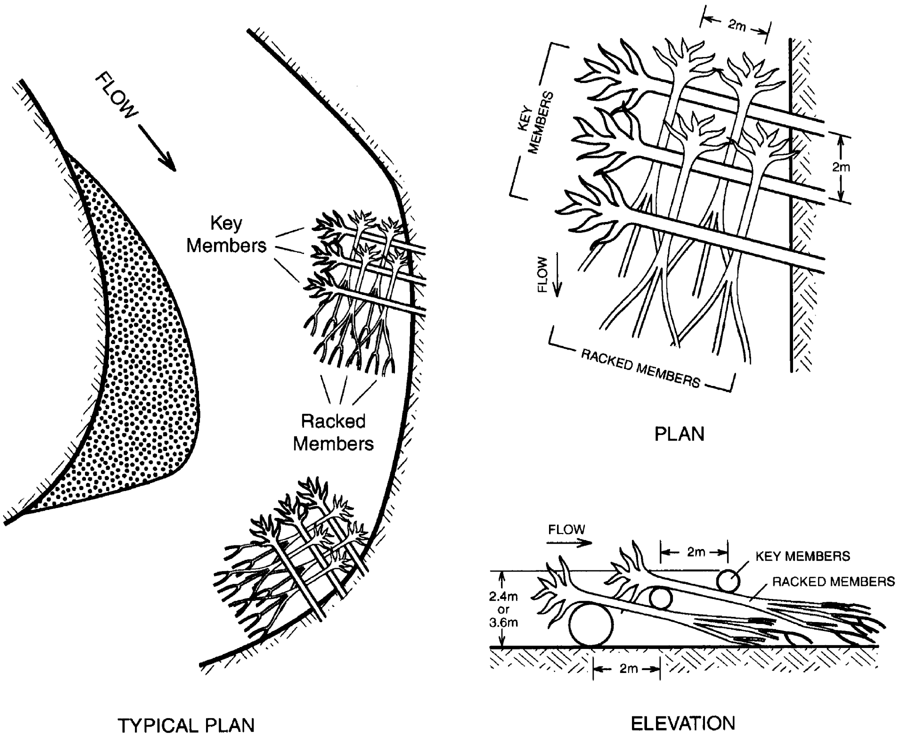


Fig. 9. Maximum observed concentrations of λ-cyhalothrin in water vs. distance downstream of injection point into agricultural drainage ditch in two simulated runoff experiments. The plotted points represent the maximum concentrations observed at any time during the experiment. See text and Table 3 for details of experiments.



TYPICAL PLAN

PLAN

ELEVATION

Fig. 10. Typical plan and elevation of large woody debris structures used for habitat rehabilitation and stabilization along incised, sand-bed stream (after Shields et al., 2000).

Stream corridors damaged by accelerated erosion associated with incision are often depauperate in woody debris relative to undamaged systems (Shields et al., 1994). Accordingly, incised stream corridors may be rehabilitated by addition of debris. In some cases debris may be added in the form of carefully designed debris structures intended to provide low-cost erosion control (Shields et al., 2001). A key aspect of the design of structures is use of a top-heavy architecture to prevent flotation until the deposition of sediment within the debris matrix (Fig. 10). Fluid drag forces also tend to displace structural members, but tend to be less important than buoyant forces in sand-bed channels. Structural stability may be increased by adding earth anchors to the design. A demonstration project constructed in 2000 featured stabilization of 2 km of a rapidly eroding channel draining 37 km^2 using 72 structures constructed at a cost of about \$80 per meter of treated bankline, which is only 19–49% of recorded costs for recent stone bank stabilization projects in this region [Personal communication: Mr. Steve Wilson, UDSA-NRCS, Grenada, Mississippi]. These costs are for the construction contract and do not include design and contract administration. Construction materials, mobilization, and profit are included. Stream bank erosion was initially checked by placement of the debris structures, and deposition of sand berms adjacent to steep, concave banks was conducive to stability during the first year following construction. Fish community structure exhibited shifts typical of other rehabilitated, incised streams in the region. However, high flows and attendant bed degradation occurring 16 and 17 months following construction resulted in progressive failure (loss of woody materials) of the structures and renewed erosion of banks (Shields et al., 2003).

4. Conclusions

Stream corridor restoration research and practice are an examples of the application of ecology and engineering to solve a class of environmental problems. Research addressing problems associated with stream

Table 4
Ecological engineering measures with potential for widespread application in agricultural watersheds

Measure	Change in current practice	Concept that may prove useful elsewhere
Management of areas upstream of gully control structures for habitat benefits	Dedication of slightly larger tracts of land for habitat; reduced frequency of vegetation removal by mowing or herbicide	Facilitating development of patches of valuable habitat in altered landscapes by minor investment in management
Management of drainage ditches to increase retention and processing of nonpoint source pollutants	Retention of vegetation in ditches. Reduction in frequency of disturbance through maintenance	Use of habitats of marginal quality as buffers to protect more valuable downstream resources
Rehabilitation of channel damaged by erosion using structures made from large woody debris	Use of large woody debris structures to accelerate natural riparian zone recovery instead of imported stone structures	Emulation and acceleration of natural geomorphic and ecological recovery processes

corridor ecosystem restoration is beset by problems that lead to poorly controlled or uncontrolled experiments. Extension of results to other sites or regions is uncertain. Social factors further complicate research and practice—riparian landowners may or may not cooperate with the experiment, and application of findings is normally through a process of suboptimal compromise. Economic issues, namely assigning costs for present and future ecosystem services that provide off-site benefits further impede progress. Three examples are offered above of ecological engineering measures with potential for extensive application in agricultural landscapes. Each represents a conceptually simple measure confined to field margins or stream corridors, thus producing minimal disruption of watershed land use. These measures may be applied at very little cost or with real savings relative to current practice. Salient features of these three measures are compared in Table 4. Clearly, engineering that solves environmental problems using an understanding of ecological processes must become more common.

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