

Review

Agricultural Effects on Streams and Rivers: A Western USA Focus

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Abstract: Globally, croplands and rangelands are major land uses and they have altered lands and waters for millennia. This continues to be the case throughout the USA, despite substantial improvements in treating wastewaters from point sources—versus non-point (diffuse) sources. Poor macroinvertebrate assemblage condition occurs in 30% of conterminous USA streams and rivers; poor fish assemblage condition occurs in 26%. The risk of poor fish assemblage condition was most strongly associated with excess nutrients, salinity and sedimentation and impaired riparian woody vegetation. Although the Clean Water Act was passed to restore and maintain the integrity of USA waters, that will be impossible without controlling agricultural pollution. Likewise, the Federal Land Policy and Management Act was enacted to protect the natural condition of public lands and waters, including fish habitat, but it has failed to curtail the sacred cows of livestock grazing. Although progress has been slow and spotty, promising results have been obtained from basin and watershed planning and riparian zone protections.



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1. Introduction

1.1. What Is the Biological Condition of All USA Streams and Rivers?

The latest national assessment of conterminous USA streams and rivers indicated that only 26–30% of the entire stream/river length was in good condition based on samples of 1924 randomly selected sites [1]. For macroinvertebrate assemblage condition determined from macroinvertebrate multimetric index (MMI) scores, it was 30% nationally (22% and 51% in the Xeric and Western Mountains ecoregions, respectively; Figure 1). For fish assemblage MMIs, those numbers were 26% nationally, 26% Western Mountains, and 19% Xeric. Nationally and west-wide, 4–58% of the stream/river length was in poor condition for total phosphorus, total nitrogen, riparian woody vegetation and riparian disturbance. The relative risk of poor fish assemblage MMI scores nationally, given a poor stressor score, was greatest for total phosphorus, total nitrogen, riparian woody vegetation, excess sedimentation and excess salinity. In the western USA, the greatest relative risks for poor fish assemblage MMI scores were for poor riparian woody vegetation, excess fine sediments, and excess salinity [2]. Using logistic regression analysis, Herlihy et al. [3] determined that poor fish MMI scores were 106 and 20.6 times as likely to occur as a result of excess salinity and excess fine sediment in the Xeric and Mountains Ecoregions of the western USA, respectively. In general, most variables for predicting both fish and macroinvertebrate MMI scores were local site variables (e.g., water quality and substrate size). However, dam density was also important for macroinvertebrates in the Xeric and Mountains Ecoregions, whereas catchment development was important for fish in the Mountains Ecoregion. Thus, a considerable proportion of USA and western USA

stream length is in poor condition because of poor water quality, excess sedimentation, and degraded woody riparian vegetation.

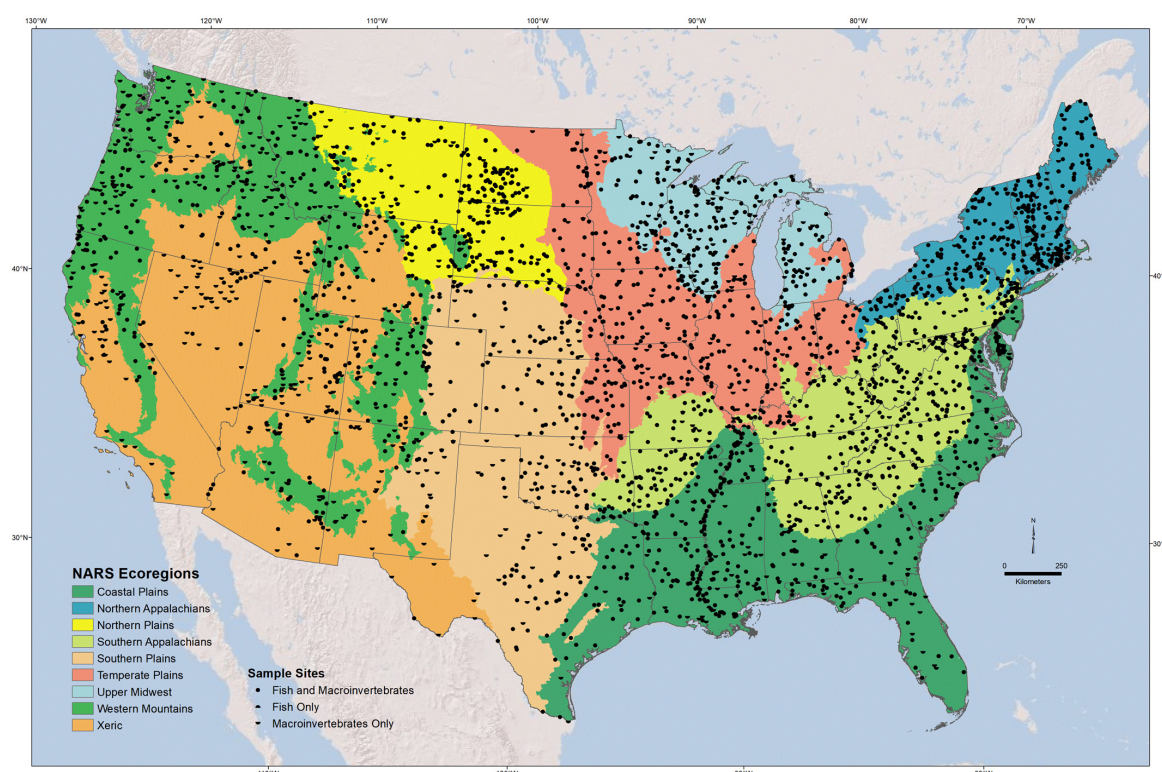


Figure 1. Locations of the NRSA sample sites and the nine aggregate ecoregions used for pattern analysis (from USEPA 2020).

1.2. What Is the Major Anthropogenic Pressure on Streams?

Nationally, agriculture was deemed the cause of 48% of water-quality impairment in USA surface waters [4]. Based on nonmetric multidimensional scaling of Bray–Curtis similarity analyses, Brown et al. [5] determined that prior agricultural or forest land use was the most important factor affecting correlations between fish and macroinvertebrate assemblages along an urbanization intensity gradient in urban streams across nine USA metropolitan areas. Chen and Olden [6], using gradient forest modeling, determined threshold changes in fish species richness and assemblage composition at 26% and 31% of catchment agriculture, respectively, for conterminous USA hydrologic units. Clearly, agricultural land uses are driving poorer water quality and poorer aquatic biotic conditions nationally.

Similar patterns are evident in the western USA. USDI [7] found that 66–78% of the riparian zones in western rangelands were damaged by livestock grazing and were in their worst condition in history. The percentage of total catchment as irrigated agriculture explained 56% of fish assemblage MMI scores, which declined with increased agriculture, in Pacific Northwest rivers [8]. Carlisle and Hawkins [9] found that macroinvertebrate assemblage condition scores were significantly lower for farm and rangeland (grazed) sites than forested sites in the western USA. Mulvey et al. [10] reported that agricultural lands accounted for 80% of the impaired stream length in the Willamette Basin, Oregon, despite representing only 30% of total stream length. Riseng et al. [11], using structural equation modeling (SEM), determined that percent catchment agriculture in the Columbia Plateau and Upper Snake River hydrologic units increased temperature and reduced flow, coarse substrate, and macroinvertebrate MMI scores. Beschta et al. [12] reported that livestock altered 939,000 km² of western USA public lands, over an order of magnitude more than is altered by roads, fire and logging combined. Perkin et al. [13], also employing SEM, determined that total catchment agriculture was associated with reduced stream

fish richness in Great Plains streams. Using random forest modeling, Hill et al. [14] determined that the most important anthropogenic predictors of macroinvertebrate MMI scores were urbanization and agriculture both nationally and in the Xeric and Mountains Ecoregions. Perkin et al. [15] reported that water diversions and aquifer pumping in the Great Plains were associated with fragmented streams and loss of 558 stream km, which in turn transformed fish assemblages from dominance by large-stream fishes to small-stream fishes. Saunders and Fausch [16] determined that riparian-derived prey in trout diets was reduced by 51–74% at increasing levels of livestock grazing compared against exclosures. Jacobson et al. [17] found that eutrophication from agriculture was the major stressor of coldwater fish habitat in Eastern Temperate Forests and Great Plains Ecoregion lakes. Based on multiple regression modeling, Kaufmann et al. (unpublished data, USEPA, Corvallis, OR, USA) determined that riparian and catchment agriculture were the most important anthropogenic pressures associated with poor streambed stability, woody riparian vegetation condition, and fish habitat cover across the USA and in the Western Mountain and Xeric Ecoregions. Therefore, agricultural land uses (including livestock grazing) are driving poorer water quality and aquatic biotic conditions in the western USA.

1.3. What Happens When Forests Are Converted to Agriculture?

Such patterns as those discussed above are particularly evident when forested regions are converted to agriculture. Leitão et al. [18], using SEM, determined that local and catchment deforestation decreased instream large wood, which reduced fish species richness and functional originality (uniqueness) in one region but not another. Percent pasture or percent agriculture were the major land uses associated with poor macroinvertebrate MMI scores in several river basins [19,20]. Threshold indicator taxa analyses revealed thresholds at 1–12% riparian forest loss and 9% total catchment forest loss for macroinvertebrate taxa [21,22], and 6–10% riparian forest loss and 1–10% total catchment forest loss for fish species [23,24]. As indicated above, even very low levels of forest and savanna devegetation can lead to the extirpation of sensitive species, which likely happened a century or more ago in the USA.

The importance of agriculture and livestock grazing to poor stream conditions is a function of three major factors. (1) Agriculture is one of the most widespread and intensive land uses (17% of the conterminous USA land area; 8% of western USA land area) [25]. (2) Rangelands are more extensive, comprising 29% of conterminous USA land area, mostly in the western states [25]. (3) Croplands are even more poorly regulated and more intensively altered than the other two major western and USA land uses: forestlands and rangelands. Thus, it is no wonder that agriculture and livestock grazing drive impairments of most USA stream kilometers—but what can be done about it?

2. Case Studies

2.1. Cropland Case Studies: Research and Management Implications

We conducted a literature search to locate at least 20 case studies each that related (1) agricultural best management practices (BMPs) to instream aquatic biotic responses and (2) livestock exclosures to instream and riparian faunal responses. As expected, most of the former studies were located in the agricultural Midwest and Southeast USA states, where row crop agriculture predominates (Figure 2). On the other hand, most of the exclosure studies were located in the western USA states where rangelands and livestock grazing predominate. Nearly half of the agricultural BMP studies involved fewer than 20 sites; 75% of the exclosure studies involved fewer than 20 sites. Only one study effectively calibrated for natural differences in catchment geology and geomorphology [26]. None of the 44 studies incorporated a probability survey design; in addition, the sampling methods and indicators were inconsistent among the studies. These sample sizes, methods, and survey constraints limit the degree to which the study results can be inferred confidently to the USA or any USA state or region [27,28]. Nonetheless, we found that several important patterns emerged from catchment and riparian BMP studies, as listed below (Table 1).

Table 1. Case studies of the effects of improved agricultural management on stream biota.

State or Region	Study Design	Sites	Mgmt. Practice	Indicators	Results	Source
Wisconsin	disturbance gradient	25	conversion of farmland to forest	fish, diatom and macroinvertebrate MMIs	increased MMI scores	[26]
North Carolina	disturbance gradient	3	conversion of farmland to forest	fish and macroinvertebrate MMIs	increased MMI scores	[29]
Michigan	disturbance gradient	23	conversion of farmland to forest	fish MMI	increased MMI scores	[30]
Wisconsin	disturbance gradient	134	conversion of unwooded to wooded riparian zones and catchments	Fish MMI	Increased scores	[31]
Minnesota	disturbance gradient	20	conversion of unwooded to wooded riparian zones	fish MMI	increased MMI scores	[32]
Michigan	disturbance gradient	23	conversion of unwooded to wooded riparian zones and catchments	fish MMI	increased MMI scores, especially for catchments	[33]
Wisconsin	disturbance gradient	38	conversion of unwooded to wooded riparian zones and catchments	fish and macroinvertebrate MMIs	increased MMI scores	[34]
Illinois	disturbance gradient	84	remove agricultural land from production	EPT taxa richness	no effect	[35]
Minnesota	disturbance gradient	3	agricultural land retirement	fish MMI	improved with riparian agricultural retirement	[36]
Missouri basin	disturbance gradient	526	conservation practices	lithophilic fish	>50% land treatment to have significant effect	[37]
North Carolina	disturbance gradient	3	erosion control	Ephemeroptera Plecoptera Trichoptera	increased taxa and EPT richness	[38]
Missouri and Arkansas	disturbance gradient	30	reduced livestock production	fish, diatom and macroinvertebrate MMIs	increased MMI scores	[39]
USA	disturbance gradient	172	conversion of unwooded to wooded riparian zones	fish MMI	increased MMI scores	[40]
Minnesota	disturbance gradient	20	conversion of unwooded to wooded riparian zones	fish MMI	Increased MMI scores	[41]
Indiana	before-after	2	re-meandering	fish	minimal and negative effects	[42]
North Carolina and Virginia	disturbance gradient	3	livestock exclusion; channel rehabilitation; agriculture BMPs	macroinvertebrates	conditions declined in 2 sites and improved in the BMP site	[43]
Wisconsin	BACI	4	agriculture BMPs	fish assemblage	improved in 1 BMP site	[44]
Ohio	BACI	16	no-till and low-till agriculture	fish MMI	significantly improved MMI scores	[45]
Illinois	disturbance gradient	9	wooded riparian buffers	fish and macroinvertebrates	abundances decreased and fish MMI scores increased	[46]
Virginia	paired	48	riparian buffers	fish MMI	scores increased	[47]
Georgia	paired	5	riparian buffers	macroinvertebrates and amphibians	scores increased	[48]

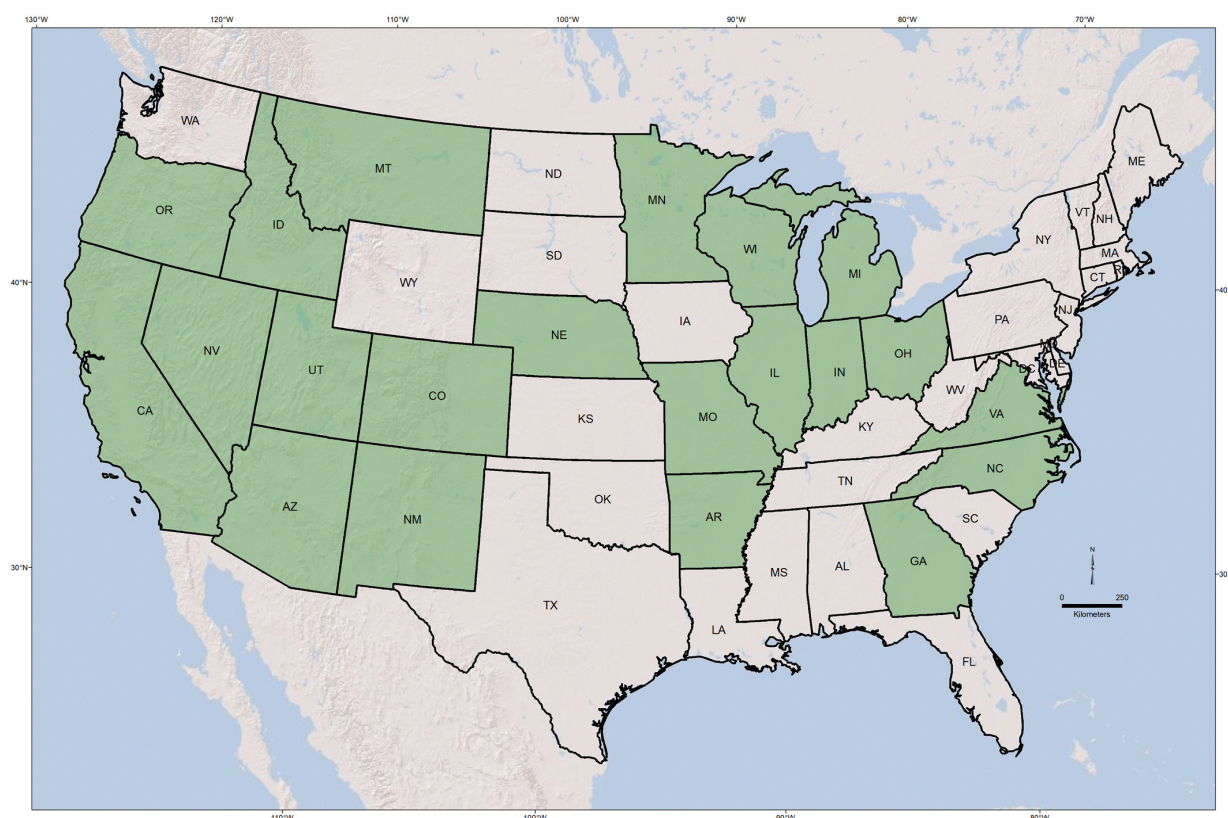


Figure 2. Locations of case study states (shaded). State abbreviations: AR (Arkansas), AZ (Arizona), CA (California), CO (Colorado), GA (Georgia), ID (Idaho), IL (Illinois), IN (Indiana), MI (Michigan), MN (Minnesota), MO (Missouri), MT (Montana), NE (Nebraska), NC (North Carolina), NM (New Mexico), NV (Nevada), OH (Ohio), OR (Oregon), UT (Utah), VA (Virginia), WI (Wisconsin).

- Both catchment and riparian treatments can affect site MMI scores [34], with the degree of those effects being a function of the relative degrees of disturbance at those two spatial extents. Where catchment conditions are intensively and extensively altered, site-specific BMPs have limited effectiveness. Where this is not the case, site-specific BMPs can produce significant improvements [41]. In other words, riparian BMPs can improve site habitat conditions, but fish assemblages cannot be recovered if there is insufficient catchment BMP implementation [31,49]. Thus, study extents matter.
- Biotic relationships with agricultural land use are very complex. Clear increases in MMI scores were apparent only after agricultural land use was less than 50%. However, even with 80% agricultural land use, some sites with relatively high gradients and rocky substrate that had not been channelized had high MMI scores [31].
- Together with historical land and water uses, unanticipated land disturbances and BMPs occurred during studies, thereby confounding the results of both BACI and disturbance gradient studies [43].
- Study durations were often insufficient to detect changes resulting from agricultural BMPs and stream-channel rehabilitation [42,43].
- Contrasting results, even from studies in the same river basin, occur because of the differing spatial extents of their study designs, together with the strengths of the relationships between stream biotic conditions and the differing effectiveness of the catchment and riparian BMP treatments expected to affect those conditions [30].
- In the Midwest, both grass and wood riparian buffers improved macroinvertebrate and fish indicator scores [50]. Therefore, it is important to consider the potential natural vegetation of riparian buffer zones rather than always planting trees (especially non-native species).

- Different indicators have different sensitivities to the same pressures or stressors [38,39]; different sensitivities to different pressures and stressors [26]; and differing sensitivities at catchment, riparian corridor, and site extents [34].
- Total taxa richness is an illusionary indicator when sensitive taxa are replaced by tolerant taxa [38]. Moreover, fish and macroinvertebrate taxa richness estimates are strongly affected by sample size and sampling effort [51–53].
- Total abundance often indicates nutrient enrichment of streams [38].

2.2. Livestock Exclosure Case Studies: Research and Management Implications

Livestock exclosure studies have many of the same constraints as catchment/riparian BMP studies that are listed above, plus others that are unique to riparian exclosures and the rangelands where most exclosure studies were located. However, we found that several important patterns emerged from catchment and riparian BMP studies, as listed below (Table 2).

Table 2. Case studies of the effects of livestock exclosures on stream/riparian fauna.

State or Region	Study Design	Sites	Indicators	Results	Source
Minnesota	disturbance gradient	17	fish and macroinvertebrates	varied more by buffer type than grazing intensity	[50]
Nebraska	disturbance gradient	6	macroinvertebrate MMI	improved scores	[54]
New Mexico	paired	4	tolerant macroinvertebrates	decreased densities and biomasses	[55]
California	paired	38	macroinvertebrates	richness increased	[56]
Oregon	paired	9	macroinvertebrates	abundance increased	[57]
Virginia	paired	10	macroinvertebrates	no significant difference	[58]
Wisconsin	paired	16	macroinvertebrates	improved scores	[59]
Minnesota	paired	26	macroinvertebrate MMI	improved scores	[60]
Oregon	paired	16	fish	increased age-0 Redband Trout densities	[61]
California	paired	7	Golden Trout	increased density and biomass	[62]
Oregon, Utah, Montana	paired	10	trout biomass	increased 184%	[63]
Idaho	paired	6	trout	abundance and size increased	[64]
Colorado	paired	3	trout biomass	doubled	[65]
Arizona	paired	6	riparian birds	increased density and species richness	[66]
Idaho	BACI	14	fish and macroinvertebrates	increased age-0 salmonid densities	[67]
Oregon	BACI	69	riparian birds	increased abundance and richness of species of concern	[68]
Oregon	BACI	106	riparian birds	increased abundance and richness	[69]
California, Idaho, Montana, Nevada, Oregon	BACI	437	riparian birds	increased abundance and richness	[70]
Oregon	BACI	9	riparian birds	increased abundance and richness	[71]
Oregon	BACI	6	riparian birds	increased abundance and richness	[72]

- Proximate paired sites on the same streams typically are not independent; rather they tend to be pseudoreplicates [73], meaning that upstream conditions may have

important biological effects on downstream conditions in an enclosure, and vice versa. Both conditions confound biological responses to enclosures [58].

- Small natural differences in channel slope, morphology and substrate may confound comparisons between the instream biological effects of enclosures versus grazed riparian zones [56].
- As with catchment versus riparian agriculture, small-sized and short-term grazing enclosures tend to be less effective measures for recovering aquatic biotic condition than livestock removal at larger spatial extents [57,59].
- Even more so than agricultural BMPs, enclosure projects have been ad hoc, not selected as part of long-term survey designs and lacking controls that could be tested efficiently [61].
- Most enclosures are too short spatiotemporally to reduce fine sediment loads and summer water temperatures sufficiently, let alone be sufficient to incorporate the riverscapes that salmonids require to successfully complete their life histories over multiple seasons and years [74,75].
- Total abundance of riparian birds frequently indicates catchment disturbance that increases abundances of wide-ranging generalist taxa [70].
- Although both macroinvertebrate and fish indicators usually had improved scores inside livestock enclosures, those responses for riparian birds tended to be stronger and more consistent (Table 2). Presumably, this occurred because of the stronger relationship between riparian vegetation and bird assemblages, and the longer durations of riparian recoveries in the avian studies.

3. Discussion

3.1. Major BMP Research and Management Challenges

There are many challenges in planning, implementing, and monitoring spatially extensive programs for improving the biotic condition of streams draining croplands and rangelands.

- Holistic, basin-extent plans for implementing and monitoring rehabilitation projects are lacking [76].
- Planning—and its monitoring and indicators—must include the geographic context and be implemented at appropriate spatial extents [76,77].
- Targeted approaches addressing entire stream lengths and their associated catchments are required to restore aquatic ecosystem integrity given the pervasive effects of croplands and overgrazing on riverscapes. Overgrazing and farming limit the degree to which significant proportions of stream networks can be rehabilitated [58,60,67]. Therefore, BMPs of multiple types should be aggregated in catchments and in proximity to streams and their floodplains to maximize effectiveness, and those BMPs must be maintained [77].
- The monitoring and indicators must be linked to specific objectives and predicted ecosystem improvements [76], and it is critical to collect quantitative pre- and post-BMP water quality, physical habitat structure and biological data, including multiple indicators for each [77].
- The survey designs, monitoring protocols, indicators and funding must be commensurate with the extent of the problem [76].
- The planning, rehabilitation and monitoring must be collaborative—not limited and parochial [76].
- That collaboration must extend to employing multiple indicators, particularly riparian birds, when assessing the effects of riparian buffers and livestock enclosures, as has been observed in lake studies [78–80].
- Greater collaboration must occur among landowners and local, state, and federal agencies that regulate land and water management in river basins, because local agencies typically lack the knowledge and authority to holistically govern up- and downstream conditions [30,81].

- Historical land uses and time lags following project implementation must be incorporated into project planning and monitoring [43,77,82]. For example, time lags following historical or current land-use changes, particularly their effects on nutrient residence times in groundwater, mean that decades are required to remove them from agricultural groundwaters feeding streams. Similarly, fine sediments and phosphorus move slowly through river networks because of storage and remobilization processes, especially in low-slope agricultural streams, where their removal may require decades to centuries [82].
- Planning for the thermal and hydrological impacts of current and future climate change is essential [77], particularly the increasing likelihood of extreme weather events, such as floods, droughts, fire and high winds.
- Livestock exclosure and stream-rehabilitation research has produced considerable scientific uncertainty because of relatively few studies, weak study designs and indicators, and insufficient consideration of the spatial extents and mechanisms of ecosystem recovery [83]. Exclosure and rehabilitation projects are generally too small and poorly located to measure aquatic indicator responses to livestock removal or BMPs accurately and precisely. Project response timing and dynamics may vary considerably with location and treatment. Sites can recover relatively quickly and predictably, recover slowly and remain more sensitive to impacts than they were before project initiation, or fail to recover at all.
- The scientific foundations for livestock exclosure and stream rehabilitation research can be improved by developing long-term, spatially extensive research programs; better project placement and study designs; and stronger commitments to pretreatment data collection [76,77,83,84].
- By altering stream catchments, humans degrade stream/riparian ecosystems in multiple ways [85]. However, fully understanding the relationships between land/stream uses and stream ecological condition is complicated by the covariation of anthropogenic and natural gradients, the differing effects of different spatial extents, and uncertainties surrounding the importance of land use legacies, physicochemical and biotic indicator sensitivities, and those indicator response thresholds [22,85–88].
- The most critical step in stream rehabilitation is cessation of the anthropogenic activities that cause degradation and hinder recovery [89]. Before implementing active rehabilitation projects, allowing sufficient time for natural recovery is recommended. Not doing so can actually exacerbate the degree of degradation and further hinder rehabilitation. Rehabilitation should be focused initially on catchments rather than riparian/stream ecosystems, assuming the catchments and their floodplains are driving degraded stream conditions [85,90].
- For projects focused on riparian zones, establish them as separate management units with different management objectives than their catchments. Limit livestock by herding, controlling the timing, intensity and duration of grazing, or permanently fencing them off from grazing. Limit agriculture to allow the potential natural riparian and floodplain vegetation to recover and monitor land use for compliance. At least on public lands, establish grazing and cropland fees commensurate with the costs of management and monitoring [91].
- Stream riparian buffer management offers largely extent-independent effects (shading, thermal controls, and organic matter and large wood additions) [92]. However, catchment management offers extent-dependent effects (nutrients and fine sediment retention, as well as flow regime) [92]. Extent-dependent effects and variations in riparian management often limit the biological responses of local riparian management. Concerted management across both spatial extents is required for full biological recovery of damaged streams. Nonetheless, the ecological benefits of wide riparian buffers along entire channel networks outweigh any potential adverse ecological effects, particularly for small streams [77,92].

3.2. What Can Be Done to Reduce Agricultural Impacts on Streams?

The science is clear. Although the objective of the Clean Water Act (CWA) is to “restore and maintain the chemical, physical and biological integrity of the Nation’s waters,” that will be impossible without controlling agricultural pollution. There are at least four key reasons why USA agriculture is so inadequately regulated under the CWA [93]. (1) Irrigated agriculture and agricultural drains are explicitly exempted from federal discharge permitting. (2) Pollutant discharges are restricted to point sources (usually pipes) versus diffuse sources, which are delegated to the states or local jurisdictions to manage via so-called BMPs. (3) Although CWA Sections 208 and 319 ask states to adopt basin-wide land use plans to control diffuse pollution, USEPA lacks the authority to determine the adequacy of those plans or to develop alternative plans, unlike what it does for point sources. In addition, local governments and landowners have resisted land use controls, federal funding for 208 planning ended in 1981, and Congressional funding for Section 319 planning and implementation is insufficient. (4) Despite its objectives, CWA enforcement still focuses mostly on water quality pollution, ignoring the substantial impacts of agriculture on physical habitat structure, flow regimes, riparian zones and biota [94–97]. For example, Ohio EPA [98] detected stream biological impairment 50% of the time that chemical criteria were met. This means that other stressors, such as physical habitat structure, limit biological condition and that biological assessments are more sensitive to landscape pressures and local stressors than are chemical toxicity criteria [1,3].

3.3. What USA Policies Might Be Implemented to Reduce Agricultural Impacts on Streams?

There are several options for how the USEPA and state and local agencies can mitigate the problems of diffuse pollution from croplands and rangelands (as well as forestlands). Under CWA Section 303, USEPA can impose water body standards (which include designated uses and the environmental criteria needed to protect those uses) on states that fail to implement those standards. However, the federal government has been reluctant to enforce that law because of its implications regarding the property rights of millions of farmers and ranchers. That Section also requires that states identify and list impaired waters that fail to meet standards and then abate that pollution, whether from point or diffuse sources by establishing total maximum daily loads (TMDLs) of the limiting pollutants. To limit those pollutants, farmers, ranchers and other landowners will need to limit nutrient, biocide and sediment runoff—most likely by limiting soil erosion and restoring riparian vegetation buffers. However, federal courts have been inconsistent in supporting such controls on pollution [93]. Furthermore, the U.S. Department of Agriculture’s Conservation Reserve Program pays farmers to remove ecologically sensitive cropland for 10–15 years, amounting to millions of protected hectares per year. Nonetheless, when contracts expire about half the land is returned to crop production [99]. The Federal Land Planning and Management Act of 1975 requires that public lands (and their waters) be managed for sustainable use, including protection of their natural condition (where appropriate), and provide food and habitat for fish and wildlife [100]. As indicated by the conditions of waters draining western USA rangelands summarized above, these requirements are infrequently met and depend on supportive federal courts for ensuring accountability (e.g., [101,102]). Increasingly, basin and watershed councils have reached consensus among landowners to implement basin- and watershed-wide management plans and TMDLs that encompass both point and diffuse sources [103–105]. In both Europe and the USA, many stream rehabilitation projects have focused on riparian protections, but few of them have been evaluated rigorously for instream effectiveness [83,106,107]. This includes a need to focus on biotic and groundwater variables, rather than just surface water-quality parameters that tend to overestimate riparian-buffer effectiveness for aquatic-ecosystem protection [83,96,108]. Clearly, if entire catchments are converted to intensive agriculture or livestock grazing, the potentials for obtaining good stream biological conditions are limited [76,77,108]. Nonetheless, protection and rehabilitation of riparian zones can increase

the probability of improved biological status in many cases [16,76,92,109,110]. Policies that encourage doing so—and discourage not doing so—are warranted.

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