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Combining Tools from Edge-of-Field to In-Stream to Attenuate Reactive Nitrogen along Small Agricultural Waterways

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Abstract: Reducing excessive reactive nitrogen (N) in agricultural waterways is a major challenge for freshwater managers and landowners. Effective solutions require the use of multiple and combined N attenuation tools, targeted along small ditches and streams. We present a visual framework to guide novel applications of 'tool stacking' that include edge-of-field and waterway-based options targeting N delivery pathways, timing, and impacts in the receiving environment (i.e., changes in concentration or load). Implementing tools at multiple locations and scales using a 'toolbox' approach will better leverage key hydrological and biogeochemical processes for N attenuation (e.g., water retention, infiltration and filtering, contact with organic soils and microbes, and denitrification), in addition to enhancing ecological benefits to waterways. Our framework applies primarily to temperate or warmer climates, since cold temperatures and freeze–thaw-related processes limit biologically mediated N attenuation in cold climates. Moreover, we encourage scientists and managers to codevelop N attenuation toolboxes with farmers, since implementation will require tailored fits to local hydrological, social, and productive landscapes. Generating further knowledge around N attenuation tool stacking in different climates and landscape contexts will advance management actions to attenuate agricultural catchment N. Understanding how different tools can be best combined to target key contaminant transport pathways and create activated zones of attenuation along and within small agricultural waterways will be essential.

Keywords: agricultural drainage ditch; denitrifying bioreactor; catchment management; nitrate-nitrogen; precision conservation; riparian buffer; stream rehabilitation

1. Introduction

Nutrient pollution from agricultural land use has degraded water quality and aquatic ecosystem health, creating significant management challenges for aquatic ecosystems around the world [1,2]. Excess reactive nitrogen (N) and phosphorus (P) inputs can cause eutrophication, toxic algal blooms, anoxic dead zones, altered food webs in receiving freshwater and estuarine environments, and nitrate toxicity in groundwater [2–4]. Small agricultural streams and ditches are the beginning of drainage systems that receive and transport excess nutrients to larger downstream waterways [5,6]. Managing N is particularly challenging due to the high mobility of N lost from the soil/plant system and the general importance of diffuse versus point sources [7,8]. While land-based nutrient reduction strategies have long been the focus of efforts to curb N loss from agricultural landscapes [9,10], in-field practices like N management and cover crops will not singly or together meet catchment water quality goals [11,12]. Nevertheless, holistic targeting of the hydrological and biogeochemical processes involved in N transport and attenuation has been challenging to achieve in practice [13]. Moreover, N attenuation practices are frequently implemented in isolation for single fields or farms and not in a targeted approach at the catchment scale [12], despite a clear need to manage N at the farm and catchment scales. Therefore, to reduce N export, in-field practices likely need to be combined with multiple tools located along terrestrial and aquatic interfaces, and within receiving waterways [14–16]. Nevertheless, despite promising modeled N export reductions by combining in-stream options with land-based N management and attenuation [15], 'tool stacking' from the edge-of-field to in-stream has not yet been evaluated in situ at the catchment scale.

We evaluate the challenges and opportunities for codeveloping tool stacking approaches to attenuate excess N from edge-of-field to in-stream environments along small, agricultural waterways. To enhance the success of multiple-scale N attenuation, we support the adoption of tool stacking that targets the 'right practice at the right place' (RPRP) [12]. Our definition of small waterways encompasses ephemerally or intermittently flowing channels to permanently inundated second-order ditches and streams that are more likely to intercept local rather than regional groundwater [17]. The RPRP framework enables conservation planners to identify locations where tool stacking or 'treatment trains' consisting of multiple tools [16,18,19] can be implemented along the various flow pathways in a catchment to maximize water quality improvements. In practice, however, the links between field-scale variability in N export (i.e., hydrological delivery pathways and timing) and N attenuation at the catchment scale are difficult to establish. Therefore, identifying and managing the drivers of N export and the impacts on the receiving environment could improve the outcomes of local solutions adopted from landscape-scale frameworks such as RPRP.

We present a visual framework to guide novel applications of tool stacking that include waterway-based options, based on N delivery pathways, timing, and impacts in the receiving environment (i.e., changes in concentration or load). The framework was developed for practitioners and researchers alike to address the most common and pervasive challenges to reducing excessive N along small agricultural waterways. Knowledge has been synthesized from a broad range of published and grey literature, field-based implementations, and research experiences. Our recommended approach emphasizes accommodating system variability, which entails fitting the hydrological landscape, including temporal and spatial inequality in N export, as well as working within the social and productive landscapes at a scale that makes a difference and at the most strategic locations along small waterways. Specifically, we focus on the importance of:

1. managing small waterways to elicit effective change in the receiving environment,
2. targeting local N export dynamics and underlying hydrological variability from agricultural land to waterways, and
3. overcoming factors limiting N attenuation with suites of edge-of-field to waterway-based tools at multiple scales and locations. We also emphasize the need to
4. encourage codevelopment of novel, effective, multiple-tool, multiple-scale waterway N attenuation approaches by scientists, practitioners, and farming communities to overcome the technical and practical challenges to managing N in agricultural landscapes.

2. Understanding and Managing for N Export Variability along Small Waterways

Focusing N attenuation actions along small waterways is likely to have the greatest effect on improving water quality at regional scales [12,20]. However, designing effectual management of these systems requires better ways to account for variability in nutrient attenuation and export across multiple scales [21–23]. By targeting the sources and locations where N can be most effectively dealt with, small waterways are especially important for influencing nutrient cycling via assimilation and denitrification [24,25]. However, active management is often required to rehabilitate the intrinsic ability of small, agricultural streams and ditches to process nutrients [26–28]. This is because channel clearance and drainage provision supersede establishing natural in-channel features to retain and cycle organic matter and nutrients [29,30]. The responsiveness of these small waterways to N management actions [24], as well as the disproportionate abundance and influence of headwaters on water quality and ecosystem processes at larger spatial scales [31,32], makes N attenuation along small waterways a promising management approach.

Dynamic patterns in N export and attenuation that change with farming practices and waterway connectivity are insidious obstacles to management [33,34]. N attenuation in small, agricultural waterways can be very dynamic, driven by fluctuations in prevailing catchment hydrology [33,35], as well as interactions with climate, vegetation, and soils [36]. Nutrient retention and processing may be higher at low discharges and warmer temperatures, while at high discharges, retention and processing can be negligible relative to the increased N flux from the land and upstream [33]. Along many agricultural waterways, fluxes of excess N 'lost' below the root zone are transported by subsurface drains or seepage channels [37–39], thus bypassing denitrification zones in shallow groundwater and riparian buffers [37,40]. Importantly, management interventions need to be effective over a range of N loading events [41] and across key N delivery flow pathways [16]. In temperate agricultural regions with waterlogged soils, peak N losses from subsurface drainage occur in the winter season after snowmelt, following heavy rainfall events, and when soil moisture conditions are saturated [33,42]. Furthermore, differences in hydrology and water chemistry from edge-of-field to in-stream nutrient sources also greatly influence N export and attenuation. Therefore, region-specific and site-specific knowledge of N export and attenuation are needed to inform optimal management outcomes at a range of scales.

Given the variable nature of the strength, times, and locations of N export from small agricultural catchments, characterizing N stocks and transport pathways in these systems can be perplexing. In particular, mapping the subsurface hydrologic pathways that transport N via shallow groundwater or subsurface drainage and quantifying their contributions to in-stream N present substantial challenges [43,44], but also opportunities for strategically targeting these with attenuation tools [45]. Similarly, delineating and targeting ephemerally or intermittently flowing swales, channels, and gullies that become hydrologically connected to waterway networks under specific hydrological conditions can be difficult, but these also present key intervention points for intercepting nutrients along critical transport pathways [46,47]. In recent years, mapping and modeling tools have improved to account for the temporal and spatial variability in waterway nutrient export and reveal how the connectivity of preferential flow pathways and transport pathways change across agricultural catchments [12,13,48]. Accounting for the contributions of small waterways to downstream N export provides a fundamental basis for improving N management [20,23], and therefore, our tool stacking framework targets attenuation tools to intercept N before it reaches larger, downstream waterways where it is more difficult and expensive to deal with.

Understanding the connectivity of N transport pathways and the variable hydrological and biogeochemical dynamics of N export in agricultural catchments and targeting these with scale-appropriate N attenuation tools using a 'systems thinking' approach pose a substantial management challenge [14,49]. A particular issue in designing approaches arises from the temporal inequality of N export caused by disproportionately high export during storm events, peak seasonal baseflows, or 'flashy' inputs along the waterway network [33,50,51]. In the case of groundwater nitrate pollution legacies seeping into streams [37,39], seasonally fluctuating shallow groundwater levels can be difficult to capture with attenuation tools [52–54]. Moreover, changes in the hydrology, water chemistry, and temperature of these inputs can together influence the microbially mediated processing rates and therefore the performance of attenuation tools [52,55,56]. For example, the efficacy of N management tools is limited by cooler water temperatures or high runoff volumes from snowmelt, particularly in cold climates [36]. The attenuation performance of a single tool can have different impacts in the receiving environment (i.e., changes in concentration or load), depending on what proportion of N is attenuated, and whether this primarily reduces mean N load or critical peaks in N concentration or N flux [57]. However, since it is generally impractical to scale tools to treat peak loading events, managers face a trade-off in dealing with such temporal inequality: either target N removal during more commonly occurring low, baseflow conditions, or design for more infrequently occurring, peak seasonal or event-driven flows that may transport a large proportion of annual loads or cause elevated peaks in concentration [51,58].

Part of the solution to this trade-off is considering whether the receiving environment is more sensitive to critical N concentration impacts, such as toxicity to aquatic organisms or enhancing the proliferation of primary producers [3], or to N loads, such as nutrient loading in many lakes or estuaries [34,59]. In flowing waters with low retention times, the ecological sensitivity and biological responses to excess nutrients are greatest when inputs co-occur with periods of peak biological demand (e.g., during low stream flows in temperate zones that coincide with warmer seasonal temperatures) and if the input controls the time-weighted concentration during these periods (e.g., baseflow conditions or long-duration, continuous inputs) [58]. In comparison, because standing waters have long retention times, nutrient inputs can accumulate and contribute to internal loading during periods of greatest eutrophication risk, irrespective of the timing, duration, or magnitude of excess nutrient inputs [58]. Hence, different attenuation tools may have different impacts throughout a catchment, depending on the type and magnitude of change in the downstream N flux [57] and based on the sensitivity and type of receiving environment.

Overall, we suggest the suitability of N attenuation tools be evaluated based on the attenuation outcome for the receiving environment, and the delivery pathway and timing of N export. The N attenuation tools that we considered are described in Table 1 and discussed in the following section. Table 1 also includes the key components of a tool stacking framework based on N delivery pathways, timing, and change in the receiving environment (i.e., effect of flux reduction on N concentration or N load) from the edge-of-field to in-stream. A visual representation of the framework to help guide decision making is presented in Figure 1, using a selection of these tools as examples.

Table 1. Overview of N attenuation tools that can be stacked across multiple locations and scales for small agricultural waterways. Tools are grouped by their location from the edge-of-field to in-stream. Potential benefits (B) and disbenefits (D), and published field study examples are provided.

Location	N Attenuation Tool	Baseflow Versus Stormflow Attenuation	Intercepted Hydraulic Flow Pathway	Effect in the Receiving Environment	Benefits and Disbenefits	Example
Edge-of-field	Exclude livestock	baseflow, stormflow	surface drains/streams, standing water, surface runoff	decreased load	B: reduced stock losses, aesthetics D: fence maintenance, alternative drinking water sources, and potential weed management issues	[60–62]
	Redirect subsurface drainage (e.g., controlled drainage)	baseflow, stormflow	tile drains	decreased load, decreased concentration peaks	B: soil water storage, flood attenuation D: requires active management	[63–66]
	Detain water (e.g., retention/detention bunds, ponds, or basins)	stormflow	standing surface water, surface runoff	decreased load, decreased concentration peaks	B: soil water storage, flood attenuation, can reduce drain clearance costs D: requires active management	[67–70]
	Retain grass filter strips and swales	stormflow	surface runoff, surface drains	decreased load, decreased concentration peaks	D: potential weed management issues	[71–73]
	Install denitrification beds or walls	baseflow	tile drains, subsurface flow	decreased load	B: little reduction of productive land D: initial flush of organic carbon, anoxic effluent, dissolved phosphorus release under anoxia, greenhouse gas production	[74–77]
Riparian buffer/floodplain	Construct or enhance wetlands	baseflow, stormflow	floods, surface drains, tile drains, standing surface water, subsurface flow	decreased load, decreased concentration peaks	B: able to cope with fluctuating water levels, stock water supply, waterfowl habitat, flood attenuation, recreation, biodiversity value, landscape aesthetics D: source of avian *E.coli*, dissolved phosphorus release under anoxia, greenhouse gas production, nutrient impacts on natural wetland ecology	[78–81]
	Disconnect tile drains to saturate riparian buffer	baseflow	tile drains	decreased load	B: soil water storage, flood attenuation D: requires active management	[40,82–84]
	Plant riparian vegetation	baseflow	surface flow, subsurface flow	decreased load, decreased concentration peaks	B: channel shading, improved aquatic habitat, wood and leaf supply to stream, recreation, harvesting of biomass, biodiversity value, landscape aesthetics D: requires some active vegetation management, shading might suppress in-stream nutrient uptake	[85–87]
Within channel margins	Reshape stream banks	baseflow, stormflow	subsurface flow, surface drains/streams, floods	decreased load, decreased concentration peaks	B: able to cope with fluctuating water levels	[24,88,89]
	Create meander bends	baseflow	surface drains/streams	decreased load, decreased concentration peaks	B: able to cope with fluctuating water levels, flood attenuation, biodiversity value, landscape aesthetics	[24,90,91]
	Create inset floodplains (e.g., two-stage channels)	baseflow, stormflow	surface drains/streams, tile drains, floods	decreased load, decreased concentration peaks	B: able to cope with fluctuating water levels, flood attenuation, biodiversity value	[92–95]
	Widen channel	baseflow, stormflow	surface drains/streams, floods	decreased load	B: able to cope with fluctuating water levels, flood attenuation D: potential sedimentation issues, weed management	[24,96,97]
	Vegetate channel or maintain in-ditch vegetation	baseflow	surface drains/streams	decreased load, decreased concentration peaks	B: forage crop for stock, biodiversity value D: potential heightened flood risk, sedimentation issues, requires active management	[98–100]
In-stream	Add in-stream geomorphic features (e.g., boulders, riffles)	baseflow	surface drains/streams	decreased load	B: biodiversity value, landscape aesthetics D: heightened winter flood risk	[24,101,102]
	Add debris dams / low-grade weirs	baseflow, stormflow	surface drains/streams, floods	decreased load, decreased concentration peaks	B: able to cope with fluctuating water levels D: heightened winter flood risk	[30,103,104]
	Add large woody debris	baseflow	surface drains/streams	decreased load	B: biodiversity value, landscape aesthetics D: heightened winter flood risk	[24,29,105]
	Add organic matter (e.g., leaves, small wood)	baseflow	surface drains/streams	decreased load	B: biodiversity value D: heightened winter flood risk	[106–109]
	Add in-stream bioreactors	baseflow	surface drains/streams	decreased load	D: initial flush of organic carbon, anoxic effluent, dissolved phosphorus release under anoxia, greenhouse gas production	[110–113]

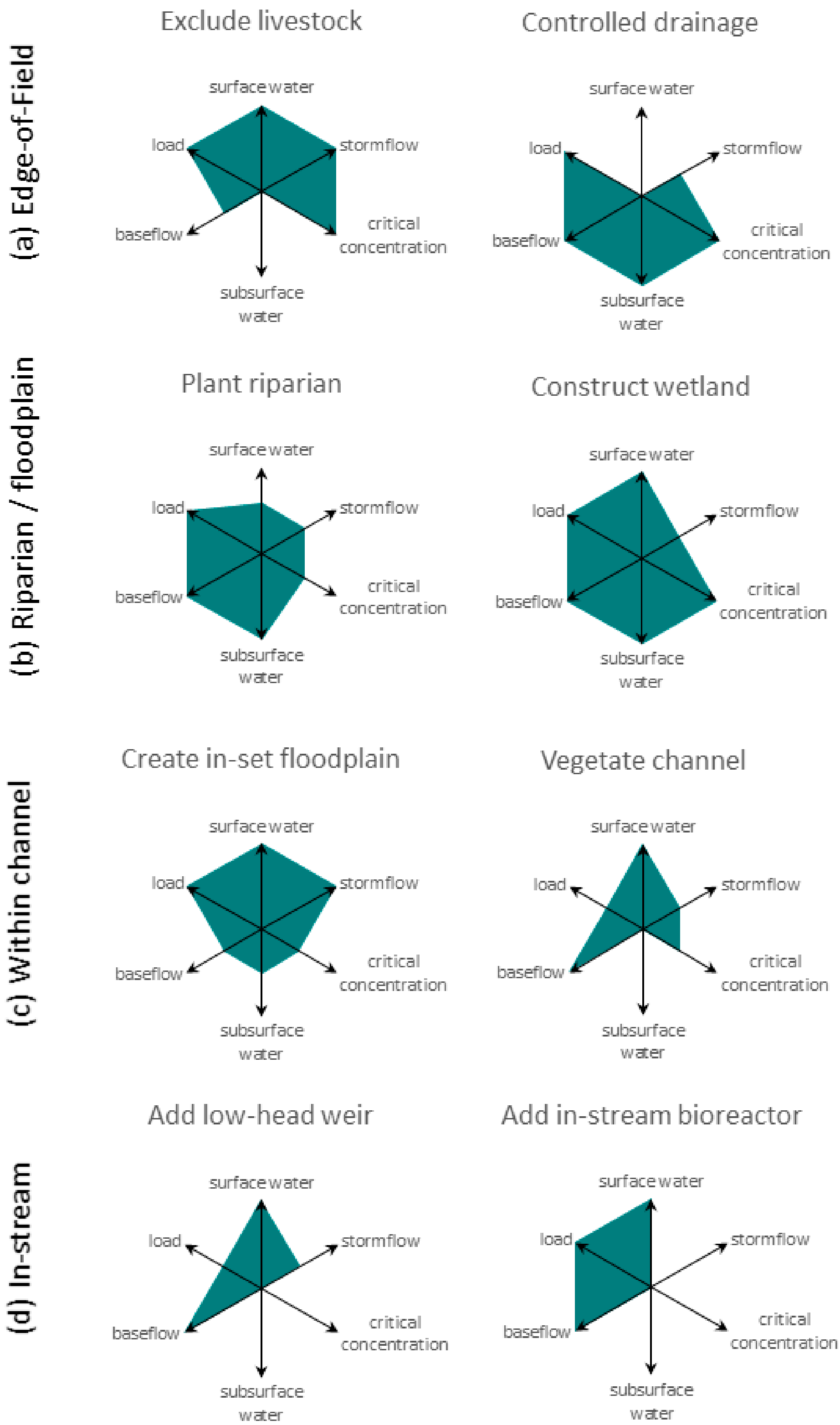

Figure 1. Potential suitability of N attenuation tool combinations across critical locations ordered from (**a**) the edge-of-field, (**b**) the riparian zone or floodplain, (**c**) within the channel margins, and finally to (**d**) in-stream. The three-axis framework (delivery pathway, timing, and change in the receiving environment) of the toolbox provides a visualization of tool stacking. Shapes denote the relative strengths for tools to target the flow pathway (surface to subsurface), timing (stormflow versus baseflow), and the effect of flux reduction on N concentration or N load in the receiving environment.

3. Expanding the N Toolbox to Boost Effectiveness from the Field Edge to In-Stream

We present a collection of tools that can be implemented to intercept N from key transport pathways and enhance attenuation at multiple locations along small, agricultural waterways, targeting a range of N export scenarios (Table 1). A 'toolbox' approach should address the prevailing drivers of N loss in a complementary fashion along waterways (Figure 1). Here, 'toolbox' refers to a suite of options that are evidence-based and can be implemented to fit the local hydrological, social, and farming contexts [12]. Given the complementarity in the hydrological-targeting and N flux attenuation (Figure 1), our framework extends current knowledge to stack tools from the edge-of-field, in riparian buffers and floodplains, within the channel margins, to in-stream [24,104,114]. Stacking different tools across these locations helps to more fully address N attenuation by not only accommodating the hydrologic flow pathways and timing, but also by enhancing N removal and retention through multiple mechanisms [115]. N attenuation mechanisms that may be boosted include physical retention, microbially mediated transformation to gases, and biological retention from assimilation, uptake, or immobilization. Tool stacking [16,18,19] should support functioning of multiple N attenuation mechanisms across locations and scales (Table 2). Moreover, implementing in-field, edge-of-field, and in-stream attenuation tools in a targeted and stacked way, focusing on small stream networks, may also provide the most cost-effective reduction of nutrient export from agricultural land to large river networks [12,116,117]. Given these potential advantages, we recommend adopting a toolbox-based N management approach that stacks multiple, different tools along and within the stream network to enhance the benefits provided by individual tools.

Table 2. Examples of how N attenuation tools can enhance multiple physical and biogeochemical attenuation processes. Tools are grouped by their location from the edge-of-field to in-stream. The attenuation mechanisms and criteria supported by tools were adopted from [24,115,118]. The degree to which tools boost these criteria is indicated as follows: + conditional/sometimes, ++ always, +++ exceptionally.

Location	N Attenuation Tool	Dominant Attenuation Mechanisms [1]	Increases Filtering, Deposition or Adsorption	Increases Water Retention Time	Enhances Surface-to -Groundwater Exchange	Increases Surface Area-to-Volume Ratio (Contact with Soil and Benthos)	Promotes Contact with Vegetation or Algae and Organic Soils or Substrates
Edge-of-field	Exclude livestock	P	+ + +				
	Redirect subsurface drainage (e.g., controlled drainage)	M, B		+ + +	+ +		+ +
	Detain water (e.g., retention/detention bunds, ponds, or basins)	P, M	+ + +	+ + +	+ +	+ +	+
	Retain grass filter strips and swales	P, M, B	+ + +	+	+	+ +	+ +
	Install denitrification beds or walls	M, P	+	+ +			+ + +
Riparian buffer/ floodplain	Construct or enhance wetlands	M, B, P	+ +	+ + +	+	+ +	+ + +
	Disconnect tile drains to saturate riparian buffer	M, B	+ +	+ + +	+	+ +	+ + +
	Plant riparian vegetation	M, B, P	+ +	+			+ + +
Within channel margins	Reshape stream banks	B, M, P	+	+		+	+
	Create meander bends	M, B	+	+	+	+ +	
	Create inset floodplains (e.g., two-stage channels)	M, B, P	+	+	+	+ +	+ + +
	Widen channel	M, B	+ +	+		+ +	
	Vegetate channel or maintain in-ditch vegetation	M, B	+	+			+ + +
In-stream	Add in-stream geomorphic features (e.g., boulders, riffles)	M, B, P	+ +	+	+		+
	Add debris dams/low-grade weirs	M, B, P	+ +	+ +			+
	Add large woody debris	M, B	+ +	+ +	+		+
	Add organic matter (e.g., leaves, small wood)	M, B	+ +	+			+
	Add in-stream bioreactors	M, P	+ + +	+ + +			

[1] P = physical retention, M = microbially mediated transformation to gases, and B = biological retention from assimilation, uptake, or immobilization.

Combining multiple attenuation tools across the key locations along the waterway network challenges the common, one-size-fits-all approach, which has often failed to improve water quality in receiving environments [119,120]. A growing body of evidence underscores the importance of managing riparian buffers and in-stream nutrient cycling to enhance attenuation through multiple pathways across a range of waterway hydrology and N export [17,114]. For example, filtering fine sediment and nutrients from surface run-off and subsurface flows in the riparian zone can enhance in-stream and hyporheic nutrient retention and removal [17,121]. Additionally, riparian vegetation can provide a source of organic matter to boost in-stream denitrification [108], as well as shading to regulate in-stream temperature and nuisance plant biomass [122,123], thereby mitigating in-stream eutrophication and responses to it [124,125]. Although riparian buffer N management approaches have become increasingly sophisticated to address multiple contaminants and provide ecological benefits to waterways [86], enhancing riparian vegetation alone may not be enough to attenuate catchment N in situations with legacy N from groundwater [39,126] or stream sediments [91], or where subsurface tile drains or seepage zones bypass riparian buffers [37,127]. Thus, to address these challenges, contemporary riparian buffer management aims to restore structural components and functions associated with saturated soils and multiple vegetation types, and enhance processing with 'treatment train' components like bunds, wetlands, and intercepting subsurface drainage [86,128]. In contrast, combinations of multiple in-stream N attenuation tools such as two-stage channels, low-grade weirs, or in-stream bioreactors are far less common [104]. This is perhaps due to the comparatively low evidence base and uptake of in-stream tools as compared to edge-of-field or riparian tools [121], or because in-stream tools without riparian- and land-based N management are scarcely effective [17]. Although several experimental studies have demonstrated how stream management interventions at different locations along small agricultural waterway networks can attenuate excess N downstream [50,53,108], further field studies are required to assess the effectiveness and potential trade-offs between the abundance and spatial locations of stacking multiple, different tools to improve water quality and aquatic ecosystem health [50,129]. In light of these knowledge gaps and research needs, it seems advantageous that N attenuation toolboxes and tool stacking be conducted collaboratively with a range of scientific experts from different disciplines, practitioners, and farming communities to identify the appropriate tools and best tool combinations for local contexts.

4. Moving Forward: Codeveloping and Implementing N Attenuation Toolboxes on Working Farms

Real-world solutions for decreasing catchment N export must fit into working farms and landscapes; therefore, the people and the place (i.e., the local social and cultural context) should also influence waterway management [130]. We encourage scientists and practitioners to engage with farmers and the farm system early in the design process, because the implementation of N attenuation tools may interfere with agricultural production, drainage provision, and drain maintenance (Table 1). Importantly, procuring environmental benefits by implementing structural N attenuation tools often competes with the productive value of agricultural land [131]. Therefore, when implementing attenuation tools from a toolbox, tool suitability must be considered, based on space or land requirements, cost-effectiveness, social acceptability, and the anticipated physicochemical, hydromorphological, and ecological outcomes [132–134]. Hence, striving to provide optimal environmental improvements to small waterways in agricultural and other productive landscapes may require compromises from landowners. Given the local context for fitting the hydrological and social landscapes and the need to balance the potential benefits and disbenefits from attenuation tools (Table 1), we stress that it will be increasingly important for scientists and managers to codevelop attenuation toolboxes. They need to be implemented collaboratively with farmers to maximize environmental and on-farm benefits, as well as minimize potentially undesirable outcomes. Moreover, landowner engagement can enrich the science and practice of waterway management, whereby farmers provide sources of local knowledge and help to build trust networks that can snowball conservation efforts within a catchment [12,131].

Codevelopment with local knowledge holders to coproduce N management solutions with scientists and practitioners will also help enhance tool uptake [135,136], but this requires effective translation and communication of the science for end-users [137]. Also, scientists and practitioners should be receptive to the local knowledge and insights that farmers can provide [138]. For example, walking along farm waterways with landowners and discussing farm and waterway management issues may reveal shared opportunities to jointly improve these by implementing suites of tools that suit the local context. This could be done by varying fenced buffer widths to encompass slumps and rills in pastures, using additional riparian plantings to fill in gaps, or implementing wetlands, bunds, or bioreactors at problematic wet spots at the edge-of-field. Therefore, we encourage that dialogue among scientists, practitioners, and farmers around selecting tool stacking combinations that best suit the local context consider how these target the delivery pathway, timing, and change in flux in the receiving environment (Figure 1; Table 1), how these enhance multiple physical and biogeochemical attenuation processes (Table 2), and the potential benefits and disbenefits (Table 1). Suitable N attenuation approaches for spring-fed waterways with stable baseflow hydrology could include saturated riparian buffers, bioreactors, and surface flow constructed wetlands to intercept tile drainage, shallow springs, or a portion of the stream water, and low-grade weirs or meanders to increase in-stream water and organic matter retention. In regions where waterways have flashier or more surface runoff-dominated hydrology, functionally based stream rehabilitation may need to involve a suite of tools designed to collect and intercept surface runoff, such as water detention bunds and sedimentation ponds, or increase hydraulic residence time and contact with the benthos across the stream channel, for example, with in-set floodplains or low-head weirs. By combining multiple tools to target a range of N loading locations and hydrological variability that limit the ability of waterways to attenuate nutrients, small agricultural waterways impacted by multiple stressors can behave more like linear wetlands [139], potentially providing greater ecosystem benefits than channelized ditches primarily intended to drain water from the landscape. Overall, this underscores the importance for land and catchment managers to 'think outside the box' by developing, implementing, and evaluating additional attenuation tools and practices at multiple influential locations on farms and within catchments.

5. Conclusions

Effective solutions to reducing excessive N in agricultural waterways require using multiple combinations of N attenuation tools, targeted along waterways at scale. Our tool stacking framework can be adopted so that field- or farm-scale management actions can be connected to water quality and ecosystem health outcomes at catchment scales. However, strategic frameworks should not replace using local hydrological data, expert judgment, and farmer knowledge, which can provide invaluable insights to help target attenuation tool stacking to fit the locations, timing, and change in N flux in headwater drainage networks. Hence, overcoming the challenges of targeting, combining, and scaling up efforts to improve how these waterways can attenuate N will require concerted efforts from scientists, practitioners, and landowners. Further research in different landscape and climate contexts is needed to demonstrate attenuation 'tool matching', where different tools are implemented at key locations along and within the stream network to attenuate catchment N. We caution that N attenuation toolboxes should be treated as adaptive management experiments rather than solutions to nutrient loading issues, while better data on the catchment- and ecosystem-level impacts of combined land- and stream-based N management actions is obtained. Using a data-driven adaptive management approach, edge-of-field, riparian, within-channel, and in-stream attenuation tools can then be combined and scaled up accordingly so that additional ecological health and on-farm impacts can be incorporated in their design and implementation.

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