Chapter 7
Vegetated Ditches for Mitigation of Contaminants in Agricultural Runoff

**Matthew T. Moore, Jerry L. Farris, Rachel L. Nifong, Erin R. Bennett,
Jason M. Taylor, Martin A. Locke, and Robbie Kröger**

Abstract The global population is expected to climb to 8.5 billion by the year 2030, and by 2050, it is projected to reach 9.7 billion individuals. Meeting the food and fiber requirements for humanity with finite land resources will require agriculture to continue to increase production while also decreasing potential impacts to natural resources. In addition to in-field conservation practices that focus on tillage reduction and planting of cover crops to prevent soil erosion, edge-of-field conservation practices that mitigate impacts of agricultural runoff are also critical to protect downstream aquatic resources. To develop edge-of-field practices that limit loss of acreage, research was initiated in the 1990s to evaluate the possibility of using vegetated agricultural drainage ditches (VADDs) to mitigate the transport of contaminants (primarily pesticides and nutrients) in runoff. This chapter includes an overview of early vegetated ditch mitigation studies conducted in the USA and the expansion of VADDs research in other countries. In this chapter, we highlight: (1) important concepts behind the use of VADDs; (2) case studies of contaminant mitigation by vegetated ditches; (3) new technologies incorporated within VADDs to further promote contaminant mitigation; and (4) challenges and future research directions. Overall, VADDs show promise for the removal of a range of pesticides and for removals of nitrogen species from agricultural runoff. Studies of phosphorus removals by VADDs show variable results, but advanced ditch designs, additional

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M. T. Moore · J. M. Taylor · M. A. Locke
USDA Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS, USA
e-mail: matt.moore@usda.gov

J. L. Farris
Department of Biology, Arkansas State University, Jonesboro, AR, USA

R. L. Nifong
Southeast Watershed Research Unit, USDA Agricultural Research Service, Tifton, GA, USA

E. R. Bennett (✉)
The School of the Environment, Trent University, Peterborough, ON, Canada
e-mail: erbennett@trentu.ca

R. Kröger
Covington Civil and Environmental LLC, Gulfport, MS, USA

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treatment technologies and harvesting of plants during senescence may improve mitigation results. Key parameters for removal efficiencies include plant densities, the length, and the hydraulic retention times of the VADD systems.

7.1 Introduction

Agriculture, including row crops, livestock, and aquaculture, is considered one of the major global contributors to water pollution. Runoff following irrigation or storm events may release pesticides, nutrients, veterinary pharmaceuticals, sediments, and other contaminants into downstream aquatic receiving systems, potentially affecting both ecosystem and human health (UNEP 2016; Mateo-Sagasta et al. 2017). Several in-field conservation practices have been proposed to decrease agricultural runoff, including reducing tillage, cover crops, crop rotation, and nutrient management. However, to adequately address the significant issue of agricultural runoff, edge-of-field practices should also be incorporated into farm management plans. Historically, edge-of-field practices have focused on establishing stiff grass hedges, riparian buffers, grass buffer strips, vegetated waterways, and constructed wetlands. While these practices have a common theme of utilizing vegetation to mitigate agricultural runoff, they also unfortunately require valuable acreage to be removed from production. For instance, constructed wetlands can be a successful strategy for mitigating the transport of contaminants within agricultural runoff (Li et al. 2021; Vymazal and Březinová 2015). However, the costs of lost production acreage might outweigh the environmental benefits (Ilyas and Masih 2017). With this consideration in mind, scientists with the Agricultural Research Service of the United States Department of Agriculture (USDA-ARS) began to seek alternative edge-of-field options to minimize loss of production acreage, while maximizing agricultural contaminant mitigation potential.

7.2 Why Ditches?

Occasionally in research, the solution to a question is already present, albeit slightly hidden by other factors. While examining the agricultural production landscape for alternative edge-of-field mitigation options, one key observation was apparent: the ubiquitous presence and proximity of drainage ditches to fields (Fig. 7.1). Although these ditches are utilized for removing excess water from cropland to prevent damage, their structure led to other questions regarding their potential use (Dollinger et al. 2015). Specifically, could vegetated agricultural drainage ditches (VADDs) mitigate agricultural runoff contaminants? Ditches meet the first requirement for an alternative mitigation option of minimal to no loss of agricultural production, since they are

Fig. 7.1 Examples of vegetated agricultural drainage ditches (VADDs) in early fall (left) and early spring (right). Representative ditches were located in Washington County (left) and Lafayette County (right), Mississippi, USA. Photos courtesy of Matthew T. Moore

already present in the landscape. Ditches also are adaptable to individual farmer or producer needs through specific sizing options and variations in vegetation among climatic regions.

Another key requirement for successful edge-of-field contaminant mitigation is a similarity in function to a constructed wetland. Wetlands are generally identified according to their hydric soils, hydroperiod, and aquatic or semi-aquatic vegetation (i.e., hydrophytes). While not all drainage ditches possess hydric sediment beds, most are of sufficient texture to hold water, since they usually are comprised of sediments from adjacent upland fields. The hydroperiod of each drainage ditch is highly variable, depending on slope, soil characteristics, amount of vegetation, and other physical and geomorphological parameters. Types of ditch vegetation are dependent on regional climatic conditions, position within the ditches (e.g., on slopes or within main channel), amount of water in the ditches, etc. As evidenced above, there is no such thing as a "typical" ditch. Attempts have been made to characterize and classify ditches based on several parameters, but those efforts were generally limited to specific regions, such as the Mississippi Delta in the USA (Bouldin et al. 2004).

Prior to the 1990s, most literature with the keywords "drainage ditch" focused on ditch ecology, including macroinvertebrates, fish, and plant communities, as well as the physical impacts (e.g., sedimentation) of runoff. Several of these studies were conducted in Europe, primarily in fens of the United Kingdom and drainage ditches within the Netherlands. Meuleman and Beltman (1993) were some of the earliest proponents of utilizing vegetated drainage ditches for protecting water quality. In their seminal work, they noted the nation-wide problem of high levels of nutrients in river water in the Netherlands. They proposed routing contaminated water through a system of vegetated drainage ditches or marshlands to utilize biological, physical, and chemical processes for nutrient removal (Meuleman and Beltman 1993). Moore et al. (2001) used this initial concept to design USDA-ARS studies which focused on pesticide mitigation. Some 20 years after these initial studies of pesticide mitigation were conducted in the USA, VADD research has been adopted in many countries around the world, including China, the Czech Republic, Germany, Finland, Italy, and Mexico (Herzon and Helenius 2008; Bundschuh et al. 2016; Moeder et al. 2017; Soana et al. 2017; Kumwimba et al. 2018; Vymazal and Březinová 2018).

7.3 Case Studies in Contaminant Mitigation

7.3.1 Pesticides

Initial USDA-ARS studies in VADDs focused on mitigation of pesticides in ditches surrounding production acreage which drained into oxbow lakes in the Mississippi Delta, USA. A 50 m stretch of a VADD in the Beasley Lake watershed, which is part of the Mississippi Delta Management Systems Evaluation Area, was dosed with a mixture of well water, the herbicide atrazine, and the insecticide lambda-cyhalothrin to simulate a storm runoff event (Moore et al. 2001). The quantities of pesticides used for dosing simulated a worst-case 5% pesticide runoff from a 0.64 cm rainfall event within a 2.03 ha contributing area. Water, sediment, and plant samples were collected at six locations within the ditch at times before, during, and after the simulated event and at locations 10 m above the inflow, at the inflow, and at 10, 20, 40, and 50 m downstream. Plant density at each sampling location was estimated, and shoot material exposed in the water column of predominant plant species (*Polygonum amphibium*, *Leersia oryzoides*, and *Sporobolus* sp.) were collected, dried, and biomass was estimated. One hour into the simulated event, 61% of atrazine concentrations measured in samples were associated with plant shoot material, while 87% of measured lambda-cyhalothrin concentrations were found in plant shoot material, indicating the importance of vegetated material for sorption of pesticides in agricultural drainage ditches (Moore et al. 2001). Using linear regression, it was determined that the concentrations of both pesticides in water could be reduced to levels below aquatic toxicity thresholds (i.e., $\leq 20\ \mu g\ L^{-1}$ atrazine and $\leq 0.02\ \mu g\ L^{-1}$ lambda-cyhalothrin) within the 50 m monitored stretch of reach, given the initial parameters for runoff and ditch flow (Moore et al. 2001).

However, a parallel ecotoxicity assessment conducted by Farris et al. (2010) indicated that toxicity persisted for 28 d post-application. Ten-day solid phase sediment exposures with larvae of the midge *Chironomus tentans* indicated persistent inhibition of survival and growth by exposures to sediments collected at all six sites in the drainage ditch. Toxicity tests with aqueous samples with the cladoceran *Ceriodaphnia dubia* and with larval fathead minnows, *Pimephales promelas*, indicated that toxicity persisted post-application at all downstream sites. Movement of the sediment-bound atrazine and lambda-cyhalothrin among lower ditch sites was reduced in comparison with the pesticide transport in aqueous samples, but still did not provide sufficient evidence to distinguish between the two pesticide effects upon observed toxicity. While acute toxicity of sediments collected from the injection site persisted throughout the study, growth impairment also observed in *C. tentans* exposed to sediments from all downstream sites. This study using temporal and spatial sampling throughout 28 d following a simulated storm event failed to identify the duration at which acute exposures to sediment would have no sub-lethal effects in standard toxicity test organisms (Farris et al. 2010).

Information gathered from that first study was used to strengthen the design of the second VADD study in 1999 conducted by the USDA-ARS, where the pyrethroid insecticide esfenvalerate was the pesticide applied in a simulated runoff event discharging into a 650 m ditch. In the study reported by Cooper et al. (2004), the pesticide was premixed with suspended sediment as a slurry before being introduced into the ditch to better simulate a storm runoff event. Spatial and temporal samples of water, sediment, and plants (*Ludwigia peploides*, *P. amphibium*, and *L. oryzoides*; only shoot material exposed in water column) were collected and analyzed for esfenvalerate. Results indicated that 99% of esfenvalerate was associated with plant material, with pesticide half-lives in water, sediment, and plants calculated at 0.12 d, 9 d, and 1.3 d, respectively. Using the linear regression model from Moore et al. (2001), it was determined that, based on initial parameters and conditions, the concentrations of esfenvalerate could be reduced to 0.1% of its original exposure concentration within a 510 m stretch of the VADD, well before entry into downstream Thighman Lake in Sunflower County, MS, USA (Cooper et al. 2004).

The third VADD study in 2000 conducted by the USDA-ARS and reported by Bennett et al. (2005) focused again on the same ditch drainage system studied by Cooper et al. (2004), except the pesticides of interest were now the two pyrethroid insecticides bifenthrin and lambda-cyhalothrin. As in Cooper et al. (2004), a water, pesticide, and suspended sediment slurry was used to deliver the simulated runoff into the ditch. Spatial and temporal sampling of water, sediment, and plants occurred throughout the VADD. Based on mass balance determinations, plants were once again the primary sink or sorption site for both insecticides. Regression modeling determined insecticide concentrations could be decreased to 0.1% of their initial value within a 280 m reach of the 650 m VADD (Bennett et al. 2005).

Following successful experiments in the Mississippi Delta, the research by the USDA-ARS of VADDs expanded to different cropping systems through collaboration with partners in California, USA, interested in utilizing this nature-based technology to address pesticide transport in runoff from various crops, such as tomatoes and alfalfa. While initially, it seemed a simple solution to transfer the VADD technology among agricultural fields, regional differences in farmer practices and state regulations posed challenges to implementation. Whereas farmers in the Mississippi Delta maintain permanent ditches adjacent to fields, many of the ditches in the tomato and alfalfa growing regions of the Central Valley of California are temporary; dug and filled in each year after harvest. Differences in the shapes of ditch channels between the two regions posed challenges concerning hydrology and potential efficacy of pesticide mitigation. Mississippi Delta ditches were generally U-shaped with gentle sloping sides and a broad thalweg, while those in California were more V-shaped with steep slopes and minimal thalweg, owing to the type of implement commonly used to construct temporary ditches. Vegetation, the primary component of VADD technology, was also an initial concern in transferring this technology from the Mississippi Delta to the California Central Valley. In the Mississippi Delta, vegetation was allowed to grow naturally in drainage ditches to serve as organic carbon sources for mitigation and microbial activity. Many of the plants found in these ditches are ubiquitous within the continental USA. However, California landowners saw them as nuisance vegetation that might provide habitat for other fauna. This concern was triggered by stricter environmental regulations in California. After consulting project partners in the US Environmental Protection Agency (US EPA) and the local Resource Conservation District (RCD) of the USDA, vegetation specific to California that alleviated nuisance or habitat creation concerns for landowners was chosen to be included in the experiments. Vegetation planted included *Hordeum vulgare* (barley) and *Lolium multiflorum* (annual ryegrass). The invasive weed *Chenopodium album* (lamb's quarter) was also prevalent within the vegetated ditches.

The initial California VADD experiment was conducted in Yolo County, where V-shaped vegetated and unvegetated ditches were constructed and dosed for 8 h with a simulated runoff of a slurry of suspended sediment and water containing the insecticides diazinon and permethrin, as reported by Moore et al. (2008). As with previous VADD experiments, water, sediment, and plant (*H. vulgare*, *L. multiflorum*, and *C. album*; shoot material exposed in water column) samples were collected temporally and spatially throughout the experiment. Pesticide half-lives and half-distances were calculated in each ditch. Half-lives were similar, ranging from 2.4–6.4 h, while comparisons of half-distances between vegetated and non-vegetated ditches showed the value of the vegetation in ditch systems. In the V ditches, cis-permethrin half-distances ranged from 22 m in vegetated systems to 50 m in unvegetated systems (Moore et al. 2008). Half-distances for diazinon ranged from 55 m for vegetated V ditches to 158 m for unvegetated V ditches (Moore et al. 2008).

A second VADD experiment in California utilized in situ vegetated field ditches surrounding both alfalfa and tomato fields in Yolo County to evaluate irrigation runoff for removals of the organophosphate insecticide, chlorpyrifos and the pyrethroid insecticide, permethrin. From alfalfa field irrigation runoff, the VADDs decreased the chlorpyrifos concentration by 20% between the ditch inflow and outflow, with 32% of measured chlorpyrifos mass associated with plant (*Leymus triticoides* and *Carex praegracilis*) material. A decrease of 67% in permethrin concentrations between inflow to outflow was measured in a ditch conveying irrigation runoff from a tomato field (Moore et al. 2011).

The California research project also had a separate ecotoxicity component to complement the measurements of chemical concentrations and load reduction in ditches draining irrigation water from tomato and alfalfa fields (Werner et al. 2010). One objective of this research was to validate the use of VADDs as a mitigation practice for selected organophosphate and pyrethroid insecticides. Early life stages of the fathead minnow *P. promelas* and the amphipod *Hyalella azteca* were deployed in custom-built exposure chambers within 400-m sections of two vegetated ditches, and in situ impairment of the organisms was intensively monitored during and after passage of chlorpyrifos and permethrin in ditch runoff. Both compounds are highly toxic to aquatic invertebrates, such as standard test organisms like *C. dubia* and *H. azetca*, while less so to *P. promelas*. The predicted toxic units (TUs) from the in-stream concentrations in runoff generally agreed with the *C. dubia* 96-h LC50 values in laboratory tests but underestimated the in situ impacts seen with *H. azteca*. Sediments collected near the ditch outflow were toxic to *H. azteca*, but no significant mortality occurred with early life stages of *P. promelas* (Werner et al. 2010). Runoff containing chlorpyrifos remained highly toxic to both species and permethrin continued to elicit toxic responses from *H. azteca*. The VADD failed to reduce pesticide concentrations below the measured effective concentration, which implied an additive or greater than additive impact from the pesticides present in tomato and alfalfa field runoff. There was a modest 15% in situ reduction in toxicity to *H. azteca* at both experimental sites. In contrast, chlorpyrifos and permethrin concentrations were 23% and 50% lower, respectively, at the ditch outflow.

Scientists with the California Department of Pesticide Regulation (DPR) examined the efficacy of a vegetated irrigation ditch to mitigate runoff of chlorpyrifos associated with alfalfa irrigation (Gill et al. 2008). The ditch (2 m width × 200 m length) was planted with several native perennial grasses such as *Dactylis glomerata*, *Agroyron trichophorum*, *L. triticoides, Elymus glaucus*, and *H. brachyantherum*. For comparison, a conventional unvegetated V ditch was similarly evaluated. Results indicated that overall, chlorpyrifos concentrations were significantly lower in the outflow of the vegetated ditch than those observed in the unvegetated ditch outflow. As irrigation events continued to occur, there was a trend of a slight decrease in the removals of chlorpyrifos, but these reductions were not significantly different among the various irrigation events. The median reduction in chlorpyrifos concentration was 38% in the vegetated ditch, while only a 1% reduction was observed in the conventional unvegetated ditch (Gill et al. 2008).

Rogers and Stringfellow (2009) further investigated the mechanisms for partitioning of chlorpyrifos between plants and sediments within VADDs using a batch equilibrium method for kinetics experiments. Plants and a homogeneous sediment mixture collected from a VADD located in Stanislaus County, CA, USA, were used in controlled experiments, and a standard soil from San Joaquin, CA, USA, was utilized as a reference comparison. Plant species examined included *Triticum aestivum, Lolium* sp., *Medicago sativa, Typha* sp., and *Juncus patens*. Sorption coefficients (K_d) were more than 10 times higher in plants (570–1300 L kg^{-1}) as opposed to soil and sediment (40–71 L kg^{-1}). Plant sorption of chlorpyrifos was in the order of *Typha* sp. > *T. aestivum* > *J. patens* > *Lolium* > *M. sativa* (Rogers and Stringfellow 2009). This study was one of the first definitive evaluations into the partitioning capacity of different species of plants. This study indicated that aquatic macrophytes (e.g., *Typha* sp.) with a high internal surface area due to porous tissues may be more effective for accumulating chlorpyrifos than hollow terrestrial plant species (Rogers and Stringfellow 2009).

Several European studies on VADDs and pesticide mitigation have been conducted in Germany and Italy. Bundschuh et al. (2016) provided an extensive characterization of aquatic fungicide exposure at base flow and during rainfall events that occurred with German viticulture, contributing to catchments at a large spatial scale. The

VADDs and vegetated detention ponds containing *Phragmites australis, Glyceria* sp., *C. elata*, *Iris pseudacorus*, *Veronica beccabunga*, *Lemna minor*, *T. angustifolia*, and *Sparganium erectum* were monitored across four seasons reduced the median fungicide concentrations and their associated ecotoxicological potential by 56% and 38%, respectively (Bundschuh et al. 2016). During runoff events, the TU approach was used within the Uniform Principle of the European Union for Tier I pesticide risk assessment. Given the properties of the mitigation systems, the short-term peaks of runoff events, and physico-chemical characteristics of the targeted fungicides (azoxystrobin, boscalid, cyprodinil, dimethomorph, myclobutanil, penconazole, pyrimethanil, tebuconazole, triadimenol, and trifloxystrobin), the reductions in measured concentrations of fungicides were consistent with the acute and chronic toxicity data for aqueous samples collected during runoff and base flow. Loads of fungicide mixtures detected during base flow indicated low risks for aquatic ecosystems. Additionally, plant coverage, water depth, hydraulic retention time (HRT), flow length of the system as well as fungicide-specific partition coefficients (i.e., Log P) explained about 55% of the variability seen in detention ponds, in contrast to similar variables accounting for only 15% of the variability in the VADD systems. The importance of plant density was emphasized in these studies, as high densities contribute to greater surface areas for adsorption and for processes involving receptors and microbial degradation (Bundschuh et al. 2016).

Otto et al. (2016) utilized a field experiment on a VADD in the Po Valley of Italy to determine whether field-measured mitigation efficiencies matched predictions generated from a fugacity model. Water containing the herbicides mesotrione, *S*-metolachlor, and terbuthylazine was pumped through the VADD, and two subsequent flushes of herbicide-free water were conducted 27 d and 82 d after the original dosing event in order to assess potential herbicide wash off. Herbicide concentrations were reduced by at least half in the VADD, regardless of the flooding conditions. In the field experiment, herbicide half-distances were approximately 250 m. However, subsequent flood events indicated that these herbicides may be remobilized after initially being sorbed to plant material, although the observed herbicide concentrations were still below drinking water limits (Otto et al. 2016).

7.3.2 Nutrients

In the early 2000s, studies by the USDA-ARS began to focus on the use of VADDs to mitigate the transport of nutrients entering the Lower Mississippi River Basin, with the aim of reducing hypoxia in the receiving waters of the Gulf of Mexico. Kröger et al. (2007a, 2008) reported on the ability of VADDs to reduce both nitrogen (N) and phosphorus (P) concentrations and loads leaving production agriculture fields in monthly baseflow and under individual storm flow conditions. Two vegetated ditches (*L. oryzoides*, *Sagittaria latifolia*, *J. effuses*, and *Echinodorus cordifolius*) surrounding fields planted in continuous no-till cotton were monitored for two years for nitrate, nitrite, ammonium, and orthophosphate. During the growing season, both nitrate and ammonium were reduced over the length of the monitored vegetated ditches while storm loads of dissolved inorganic N were reduced by 57% (0.84 kg ha^{-1} yr^{-1}) by the VADDs (Kröger et al. 2007a). Phosphorus mitigation proved to be seasonal, with the ditches alternating between a P sink and a source. Annually, the ditches reduced the maximum inorganic P load leaving the ditches by approximately 44% (Kröger et al. 2008).

Expanding upon studies by Kröger et al. (2007a, 2008), two agricultural ditches (one vegetated, one unvegetated), similar in size, landform, and location in the Mississippi Delta were utilized by Moore et al. (2010) to determine nutrient mitigation during a simulated storm runoff event. No significant differences were observed between the two ditches in reductions of nitrate, ammonium or dissolved inorganic P between the inflow and outflow. Total inorganic P loads were reduced by 71 ± 4% in the non-vegetated ditch, while there was only a 36 ± 4% reduction in the vegetated ditch (Moore et al. 2010). The reductions in phosphorus loads were not unexpected in the unvegetated ditches, since sediments can provide significant P binding potential. Kröger and Moore (2011) examined P dynamics in drainage ditch sediments across a range of sites within the Lower Mississippi River Basin. Their results indicated most drainage ditch sediments had low immediately bioavailable P, with a degree of P saturation of <20% (Kröger and Moore 2011). However, since these ditches had low P binding energy (0.34–0.60 L mg^{-1}) and low P sorption maxima (17.8–26.6 L mg^{-1}), they may not necessarily serve as P sinks. These results highlight the challenges for VADD nutrient mitigation within ditches. Results are often highly variable, depending on local conditions. Collins et al. (2016) utilized in situ mesocosms in two ditches on a cattle ranch in the Everglades region of Florida, USA to examine P sorption potential. One ditch had an organic sediment and was vegetated with *Pontederia cordata*, while the second ditch had a mineral sediment and was vegetated with a mixture of *Eichhornia crassipes* and *L. minor*. Results indicated P uptake was greater and was also subsequently released more rapidly in the vegetated ditch. It was determined that vegetated ditch residence time (0.46 and 0.11 days) was insufficient to promote mitigation of P, and an extension of residence time would benefit P mitigation (Collins et al. 2016).

Taylor et al. (2015) utilized mesocosms to explore the VADD concept and attempt to differentiate mechanisms which may be affecting N mitigation. Using three treatments (unvegetated control), rice cutgrass (*L. oryzoides*), and common cattail (*T. latifolia*), they examined the N mitigation capability of treatment systems, while also quantifying denitrification rates in each system. Systems with *L. oryzoides* retained 68% of nitrate loads in simulated runoff exposures, while *T. latifolia* and unvegetated controls retained 60% and 61%, respectively. Sediment cores removed from mesocosms planted in *L. oryzoides* had significantly higher mean denitrification rates (5.93 mg m^{-2} h^{-1}) than either *T. latifolia* or unvegetated controls (0.2 mg m^{-2} h^{-1} and −0.19 mg m^{-2} h^{-1}, respectively), indicating the strong potential for permanent removal of excess N through microbially mediated denitrification (Taylor et al. 2015).

Soana et al. (2017) utilized reach scale methods and laboratory incubations to estimate plant nutrient uptake in a study within the Po River plain of northern Italy.

N removal, primarily via denitrification, was greater within vegetated ditch reaches (38–84 mmol N m^{-2} d^{-1}) than in unvegetated reaches (12–45 mmol N m^{-2} d^{-1}), as reported by Soana et al. (2017). Castaldelli et al. (2018) utilized mesocosms to evaluate denitrification in systems vegetated with *P. australis* and unvegetated systems under a range of runoff flow velocities (0–6 cm s^{-1}). Results indicated that vegetated sediments had more denitrification activity (27–233 mmol N m^{-2} d^{-1}) than did unvegetated sediments (18–33 mmol N m^{-2} d^{-1}), as reported by Castaldelli et al. (2018). Likewise, nitrate removal and denitrification rates increased by an order of magnitude when the water velocity increased from 0 to 6 cm s^{-1} in the vegetated systems. Zhang et al. (2016) conducted a field-scale experiment examining ammonium removal and reduction of nitrous oxide emissions in ditches vegetated with *P. cordata* and *Myriophyllum elatinoides* versus unvegetated ditches. Results indicated that vegetated ditches increased ammonium removal while simultaneously decreasing nitrous oxide emissions (Zhang et al. 2016). Dominant ammonium removal pathways differed between the two plant species, with *M. elantinoides* vegetated ditches achieving removal primarily by plant uptake and by nitrification–denitrification processes mediated by microbes. Alternately, unvegetated ditches and those vegetated with *P. cordata* removed ammonium via sediment sorption (Zhang et al. 2016).

Soana et al. (2018) conducted mesocosm experiments to elucidate nitrate mitigation via denitrification within microbial biofilms colonizing dead *P. australis* stems during winter. Using chlorophyll *a* content as a proxy for the proportion of the autotrophic community on the biofilm, Soana et al. (2018) reported *P. australis* vegetated sediments were more efficient in conversion of nitrate through denitrification (7–17 mmol N m^{-2} d^{-1}) than were unvegetated sediments (3–5 mmol N m^{-2} d^{-1}). Results of this study indicated the best practice for ditch maintenance was to postpone mowing until the end of winter to promote nitrate removal throughout the year (Soana et al. 2018). Soana et al. (2019) conducted watershed modeling within the lowlands of the Po River Basin in Italy to determine nitrate mitigation through denitrification and the effects of ditch maintenance (mowing) within the watershed. Based on the current maintenance techniques, 11% of excess N was removed from the system (3300–4900 t N yr^{-1}). However, this could be improved to 4000–33,600 t N yr^{-1} if 90% of vegetated ditches were maintained (Soana et al. 2019). Additional gains in denitrification could be made by delaying ditch mowing at the end of the growing season, as pointed out previously by Soana et al. (2018).

Kumwimba et al. (2016) examined the nutrient mitigation capacity of six plant species, *Canna indica*, *Cyperus alternifolius*, *Colocasia gigantea*, *Acorus calamus*, *I. sibirica*, and *M. verticillatum*, and reported removal efficiencies ranging from 97–99%, 98–100%, and 90–98% for total N, ammonium, and total P, respectively. They also noted an 85–95% increase in aboveground biomass as plants sequestered nutrients, but a rapid nutrient loss occurred after 70 d during the senescent period (Kumwimba et al. 2016). Harvesting of plant biomass prior to senescence was suggested as a possible remedy for preventing nutrient release back into the vegetated ditch system. Kumwimba et al. (2020) examined VADD ability to retain nutrients during periods of low temperatures in China. Overwintering plants in the VADD included *A. gramineus*, *M. aquaticum*, and *I. sibirica.* Approximately 43–46% of N species were retained, with 46–52% of P species being retained by the VADD in low temperatures. It was estimated that 5.37×10^3 kg N y^{-1} and 0.65×10^3 kg P y^{-1} were removed by the VADD. Further plant senescence did result in release of nutrients during the experiment, so caution in design was noted (Kumwimba et al. 2020). Other studies have also demonstrated the potential for nutrient release during plant senescence but relied on experiments designed to represent worst-case scenario by using chambers with plant material and water only to estimate nutrient release rates (Peverly 1985; Kröger et al. 2007b; Menon and Holland 2014; Wang et al. 2018). In contrast, Taylor et al. (2020) measured P release from senescent plant material in mesocosms during rain events throughout winter. Mesocosms representing intact ecosystems with sediment, root systems, senescent plant biomass, and associated microorganisms demonstrated balanced retention; that is, import during the growing season and export during the senescent period when exposed to low P loads. However, mesocosms receiving high P inputs had high retention (80–90%), which could be partially explained by excess P being translocated to extensive root systems in mesocosms (Taylor et al. 2020).

7.3.3 Complex Mixtures

Early studies of VADDs by the USDA-ARS focused on a particular contaminant class, such as pesticides or nutrients. However, ditches receive a variety of contaminants, many of them simultaneously. Several studies have examined overall VADD efficiency regarding complex mixtures of contaminants. In a mesocosm experiment, Moore and Locke (2020) examined the capacity of typical plant species in VADDs, *M. aquaticum*, *P. amphibium*, and *T. latifolia* to remove nutrients (orthophosphate, nitrate, and ammonium) as well as three pesticides, clomazone, propanil, and cyfluthrin during a simulated runoff event. The target inflow concentration for each nutrient species was 10 mg L^{-1}, while pesticide inflow concentrations were 20 μg L^{-1} for both propanil and clomazone and 10 μg L^{-1} for cyfluthrin. The simulated storm event was applied to individual mesocosms for 6 h (representing the HRT), followed by 48 h with no flow, a then a 6 h flush with unamended (no nutrients/pesticides) water. Samples were collected temporally throughout the experiment and load reductions were calculated. In the vegetated mesocosms, mean percent load reductions for orthophosphate, ammonium, and nitrate ranged from 39–52%, 47–62%, and 50–59%, respectively, while in the unvegetated mesocosms, mean percent load reductions were 42%, 52%, and 54% for orthophosphate, ammonium, and nitrate, respectively (Moore and Locke 2020). Cyfluthrin retention varied only slightly between the unvegetated (76%) and vegetated systems (ranging from 79–86%). Similar results were noted for propanil, with 69% retention in unvegetated systems, while retention in vegetated systems ranged from 63–71%. Mesocosms vegetated with *P. amphibium* were most efficient at retaining clomazone (63%), followed by mesocosms vegetated with *T. latifolia* (44%), *M. aquaticum* (8%), compared to 5% retention in the unvegetated system (Moore and Locke 2020).

Kumwimba et al. (2021) evaluated the effectiveness of VADDs in rural China to mitigate nutrients and metals from rural wastewater, as well as identifying the standing stock concentrations in associated vegetation (*M. verticillatum*, *Acorus gramineus*, *Thalia dealbata*, *C. alternifolius*, *Hydrocotyle vulgaris*, *I. pseudacorus*, *C. gigantea*, *P. australis*, *A. calamus*, and *C. indica*) N and P species were reduced by 48–63% and 51–58%, respectively. Additionally, Ni, Cu, Cr, Zn, Cd, Pb, As, Fe, Al, and Mn were reduced by 50%, 56%, 63%, 79%, 67%, 80%, 60%, 52%, 19%, and 24%, respectively (Kumwimba et al. 2021). The primary location of metals in the plants was in either in the stems or roots, with Al, Fe, and Mn having the highest recorded concentrations. Based on their data, Kumwimba et al. (2021) determined plant biomass harvesting in either August or early September was optimal for effective metal removal in the VADD.

In Mexico, Moeder et al. (2017) studied a 3.6 km section of a VADD in Sinaloa State receiving both agricultural runoff and discharges of domestic wastewater from a nearby community. Five different points along the ditch were monitored on a monthly basis for 38 different pollutants, including pesticides, polycyclic aromatic hydrocarbons, artificial sweeteners, and pharmaceuticals. Sediment and plant samples were collected three times during the year and also measured for concentrations of pollutants. Results indicated that cattails (*T. domingensis*) absorbed 10 of the 38 measured pollutants and sediment sorption was of minimal influence. It was hypothesized that microbial activity and the subtropical climate contributed to effective pollutant mitigation within the VADD.

Vymazal and Březinová (2018) monitored a 200 m VADD for two years in the Czech Republic to examine its ability to mitigate levels of N and P, suspended solids, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Ditch vegetation was dominated by *P. australis*, *T. latifolia*, and *Glyceria maxima*. N and total P removal were estimated at 1,070 kg ha^{-1} y^{-1} and 804 kg ha^{-1} y^{-1}, respectively. Fourteen percent of removed P load was attributed to plant uptake (Vymazal and Březinová 2018). Removal of suspended solids, BOD, and COD were 2,0437 kg ha^{-1} y^{-1}, 1,500 kg ha^{-1} y^{-1}, and 7,000 kg ha^{-1} y^{-1}, respectively. Nitrogen and organic removal were influenced by temperature, whereas P and suspended solids removal were not affected by temperature (Vymazal and Březinová 2018).

7.3.4 New Technologies in VADDs

A common misconception is that by utilizing an individual conservation practice, one can solve all the environmental issues for a particular location. While individual practices can certainly have a significant impact, suites of various conservation practices typically provide improved mitigation efforts needed to meet environmental goals.

The capacity of VADDs to mitigate contamination from agricultural runoff is well-documented in the literature and is summarized in this chapter, but VADDs cannot to be considered a "silver bullet" for mitigating all agricultural runoff. Instead, it should be viewed as a valuable tool in a larger toolbox. Goeller et al. (2020) provides an excellent resource for "tool stacking" for N mitigation. They describe various N mitigation tools that can be implemented at multiple locations within a watershed for better nutrient attenuation. Locations of these mitigation measures include in-stream, within channel margins, riparian buffer and floodplains, and edge-of-field tools. Below is an overview of both old and new technologies that have been incorporated within VADDs that demonstrate the same "tool stacking" concept.

Perhaps the best example of technologies incorporated within VADD is research recently published by Phillips et al. (2021) describing an integrated vegetated treatment system (VTS) which included a sediment trap, vegetated ditch, compost swales, and a granulated activated carbon (GAC) or biochar polishing filter. Each component of the VTS was designed with a specific purpose in mind: coarse particulates would be removed by the sediment trap, while suspended sediment and insecticides would be removed by the vegetated ditch and compost swales. Any residual pesticides remaining would be treated by sorption using either GAC or biochar. Additionally, irrigation water for these experiments was treated with polyacrylamide (PAM), a long-chain polymer commonly used for erosion control, to minimize concentrations of suspended sediments. Both simulated and actual runoff events were examined for the ability of VTS to reduce concentrations and loads of the neonicotinoid insecticide, imidacloprid [1-(6-chloro-3-pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine] and the pyrethroid insecticide, permethrin. In the series of simulated runoff events, the VTS reduced the suspended sediment, imidacloprid, and permethrin concentrations by 30–82%, 88–92%, and 98–100%, respectively, in tests with the GAC polishing treatment. With a biochar polishing treatment, concentrations of suspended sediment, imidacloprid, and permethrin were reduced 42–85%, 89–94%, and 98–99%, respectively (Phillips et al. 2021). Following VTS treatment and GAC polishing, loads of suspended sediment, imidacloprid, and permethrin were reduced by 63–95%, 94–98%, and 98–100%, respectively. When biochar was substituted for the polishing step, load reductions were 82–96%, 98–99%, and 99–100%, respectively, for suspended sediment, imidacloprid, and permethrin. When actual runoff events from a lettuce field were routed through the VTS, concentrations of suspended sediment, imidacloprid, and permethrin were reduced by 78–84%, 74–80%, and 48–100%, respectively. Load reductions for these same events were approximately 98%, 99%, and 97%, for suspended sediment, imidacloprid, and permethrin, respectively (Phillips et al. 2021).

Addition of physical structures in VADDs have also been suggested to improve mitigation of agricultural runoff. Flora and Kröger (2014) examined in a mesocosm experiment the value of constructing low-grade weirs to VADDs containing *L. oryzoides* and *T. latifolia* that receive aquaculture pond effluent. In systems without weirs, there was a decrease in TP, total ammonia nitrogen (TAN), and nitrate loads of 47%, 43%, and 63%, respectively, but there was also a 154% increase in the loads of soluble reactive phosphorus (SRP). In VADDs with low-grade weirs, decreases of

SRP, TP, TAN, and nitrate loads were 80%, 86%, 89%, and 89%, respectively (Flora and Kröger 2014). Low-grade weirs increased the HRT by 32% and decreased flow velocity, which likely contributed to decreases in nutrient loads exiting the system. Iseyemi et al. (2018) reported that VADDs with weirs had significantly lower bioavailable P (0.018 mg g^{-1}) than VADDs without weirs (0.021 mg g^{-1}). Mean P sorption maxima ranged from 139–671.8 mg kg^{-1} in the summer to 525–1288 mg kg^{-1} in winter, with P binding energy measurements ranging from 0.63–1.34 L mg^{-1} in the summer to 0.09–0.30 L mg^{-1} in the winter (Iseyemi et al. 2018). Kröger et al. (2011, 2012) found the use of low-grade weirs created zones upstream which allowed for sedimentation to occur and further improved denitrification and bound P removal.

Faust et al. (2018a) provided a review of enhanced mitigation methods utilized in VADDs, in addition to VADDs alone. Riser and slotted board pipes had some reported success in decreasing nitrate loads in tile drainages, typically in northern and eastern states of the USA, but they noted limited evidence of the ability of these structures to enhance removals of ammonia, TN, TP, or total suspended solids (Faust et al. 2018a). Another physical structure similar in concept to VADD is the two-stage ditch. These special ditches are often used in the Upper Mississippi River Basin in the USA, and the “benches” created in these systems may serve to increase denitrification levels (Mahl et al. 2015; Powell and Bouchard 2010; Roley et al. 2012; Speir et al. 2020).

Faust et al. (2018a, b) also discussed incorporation of organic carbon amendments (if limiting) in VADDs with physical structures, such as weirs, as an additional step toward increased denitrification in these systems. Organic carbon amendments may include various wood media, corn stover (leaves, stocks, and cobs left over after harvest), rice straw, or Bermuda grass hay (Faust et al. 2018a). Eighty-nine drainage ditch sediments were collected from 35 sites throughout the Lower Mississippi Valley, USA, to determine baseline organic carbon and N content, finding organic carbon content ranging from 0.253% to 6.04% (Faust et al. 2018b). These contents are well below sediment organic carbon expected in restored and natural wetlands, so organic carbon may be limiting denitrification in Lower Mississippi Valley drainage ditches. Nifong et al. (2019) used a flow through, intact sediment core experiment to assess the effects of gypsum or hardwood mulch overlying layers on ditch sediment denitrification. Sediment denitrification rates were 0.6, 1.3, 9.2, and 11.2 mg N_2-N m^{-2} h^{-1} for control, gypsum, mulch-gypsum, and mulch cores, respectively. Mulch and mulch-gypsum treatments were estimated to remove 65 and 69% of N loads, respectively (Nifong et al. 2019). Cai et al. (2021) examined amendments with rice straw and the mineral zeolite (independently and in combination) in bench-scale experiments designed to improve N removal in drainage ditches receiving either high ammonium or high nitrate concentrations with low carbon content. Ammonium removal rates were greatest in the rice straw-zeolite combination (48.9–77.7%), as were nitrate removal rates (67.6–82.7%). The presence of microbial denitrifying genes (*nirK*, *nirS*, *narG*, and *napA*) was significantly enhanced in the rice straw-zeolite mixture, contributing to the improved nitrate removals (Cai et al. 2021).

Studies have also evaluated various VADD amendments for improved removal of P compounds. He et al. (2021) studied the use of akadama clay (particle size

1–6 mm) barriers in mesocosm-scale experiments as a method of removing phosphate in VADDs. Akadama clay is a reddish-brown granulate derived from volcanic sources in Japan, although it is exported around the world. Highest P removals were in VADD mesocosms with akadama clay barriers that had the following characteristics: akadama particle size of 1 mm; 10 cm height; and 90 cm length. Removal efficiencies were 97.1% for TP, 96.9% for particulate P, and 97.4% for dissolved P (He et al. 2021). While not specifically examining VADDs, Penn et al. (2007) did address several P sorbing materials that could be used to mitigate drainage ditch water. Materials suggested included limestone, byproduct gypsum, quick lime, and alum. They noted several factors including material cost, availability (including transportation), potential contaminants, physical properties, and P sorption characteristics as issues of concern for choosing a P sorbing material. When examining the physical properties of sorbing materials, it was noted that an acidic pH is most effective for P sorption with Al and Fe complexes, while Ca and Mg are more effective at pH 6–7.5 for precipitation of P (Penn et al. 2007). How these sorbing materials are implemented was also addressed, including the potential of "flow dosing," broadcast application, or the use of flow through structures, such as filter socks (Penn et al. 2007).

7.3.5 Challenge: VADD Maintenance

Maintenance of VADDs is by far the most common challenge of concern to both researchers and landowners. Routine ditch maintenance, including dredging, mowing, chemical weeding, and burning is necessary for flood attenuation and to maintain proper flow. How often and to what degree maintenance must occur is a critical knowledge gap. This is not merely a simple engineering issue of hydraulics. If VADDs are utilized for drainage and contaminant mitigation, a balance must be maintained to allow sufficient water flow, while still providing vegetation and other organic carbon sites for binding of nutrients and pesticides. Dollinger et al. (2015) reviewed drainage ditch design and maintenance, noting the key parameters for maintaining ecosystem services in VADDs were the degree of vegetated cover, ditch morphology, reach connections, and slope orientation. They similarly noted that the geochemical, geophysical, and biological processes providing these ecosystem services varied widely with different ditch characteristics, but in general, there were low adverse effects on biodiversity conservation and water purification abilities if VADDs were mowed during the proper season (Dollinger et al. 2015). Iseyemi et al. (2019) examined carbon sequestration capabilities of mowed and unmowed VADDs (with and without weirs) in summer and winter experiments. Average carbon content in mowed and unmowed ditches was 16.54 ± 0.52 and 16.60 ± 0.44 g kg^{-1}, respectively in summer, while winter averages were 15.86 ± 0.71 g kg^{-1} and 14.89 ± 0.77 g kg^{-1}, respectively for mowed and unmowed ditches. These results indicate no difference in maintained and unmaintained ditches regarding average carbon content (Iseyemi et al. 2019).

Another issue with VADD maintenance deals with the question of plant senescence. If plants take up excess nutrients during the growing season, what happens when the plants die? Will those nutrients then be released back into the ditch, nullifying any potential mitigation to downstream aquatic resources? Kröger et al. (2007b) examined this question by studying microcosms filled with harvested *L. oryzoides* plants in decomposition bags soaked in a control water of known nutrient composition. Treatments examined included enriched *L. oryzoides* samples (those exposed to 3.8 g m^3 of N and P), *L. oryzoides* samples from a reference ditch with no enrichment, and control microcosms with only water and no *L. oryzoides* plant samples. Decomposition and leaching were monitored for a 12-week period from December until February. Senescence of the enriched *L. oryzoides* samples resulted in higher concentrations of P present in microcosm water (2.19 ± 0.84 mg P L^{-1}) (Kröger et al. (2007b). Taylor et al. (2020) further elucidated N and P dynamics in larger mesocosms observed during both the summer growing and winter decomposition seasons using *L. oryzoides* as the model plant. Throughout the experimental seasons, both measured N retention and modeled denitrification rates did not vary between treatments; however, retention of P increased significantly with P enrichment treatments. They also reported winter export of N was less than 10% of the observed summer N uptake, and denitrification was likely responsible for approximately 40% of retained N. In mesocosms that lacked P enrichment, there was only 25% retention in the winter, while net P retention increased from 77 to 88% as enrichment treatments increased (Taylor et al. 2020).

Furthermore, a recent study by Martin et al. (2021) illustrated that greater bed and bank vegetative coverage in VADDs provided improved water quality when comparing upstream and downstream sites, while showing that nutrient values were higher in the non-production season relative to the production season. This further illustrates the importance of vegetation density and the potential negative mitigative effect due to senescence, indicating that VADD seasonality requires consideration when utilizing this mitigation strategy.

7.3.6 Future Directions

Vegetated agricultural drainage ditches hold significant promise as effective edge-of-field contaminant mitigation sites, even though results may vary by field, region, and contaminant due to a myriad of factors. Kumwimba et al. (2018) published a review of VADD designs, various management strategies, and other mechanisms which affect retention of contaminants in agricultural runoff, as well as components of domestic sewage. These authors highlighted the importance of vegetation, ditch substrate, and microbial activity as three key parameters for individual VADD success. Suggestions for future VADD research included further investigation on the effect of size, length, and slope of VADDs, vegetative cover and type, ditch substrate, microbial biofilms, organic carbon amendments for denitrification, impacts of low-grade weirs, and various maintenance practices for vegetation and substrates (Kumwimba et al. 2018).

While several aspects of nutrient mitigation were discussed in this chapter, the future direction of VADD research with regard to nutrients will likely gravitate toward studies that integrate spatial and temporal patterns in processes. For example, using the principles developed for stream metabolism (Hall and Hotchkiss 2017), research focused on agriculture can begin to understand linkages between biological processes and nutrient mitigation in VADDs. Recent USDA-ARS research utilized sensor measurements (i.e., dissolved oxygen and temperature loggers) and hourly sampling in artificial streams vegetated with *L. oryzoides* to determine N and P uptake, gross primary productivity (GPP), ecosystem respiration (ER), and denitrification (Nifong et al. 2020a; Nifong and Taylor 2021). Vegetated ditches had significantly higher N uptake rates and removal (2 h: 63%, 4 h: 44%, 6 h: 32%) than unvegetated ditches (2 h: 32%, 4 h: 21%, and 6 h: 17%). In vegetated ditches, GPP and ER were significantly higher, and an increased HRT resulted in increased respiration rates (Nifong and Taylor 2021). Studies of this magnitude, while more complex than simple measurements of inflow versus outflow, provide key details in mechanisms and expectations for nutrient mitigation in VADDs. Similar approaches based on diel patterns in dissolved N_2 gas are being explored to integrate denitrification estimates across temporal and spatial scales within ditches (Nifong et al. 2020b).

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