White Paper on

VEGETATIVE BUFFERS

Paul F. Hoekstra[1], Carol Hannam[2]

[1]Syngenta Canada Inc., Guelph, Ontario

[2]Synthesis Agri-Food Network, Guelph, Ontario

October 31, 2017

A Report to the Agriculture and Agri-Food Canada Multi-stakeholder Forum (Mitigation Working Group) for Neonicotinoids

TABLE OF CONTENTS

Introduction

What are Vegetative Buffers?

Vegetative buffers (also referred to as vegetative filter strips) are a practical and environmentally friendly solution to minimize soil erosion and off-target field movement of chemicals (including pesticides) (1-3). These specially constructed areas of permanent vegetation within and between agricultural fields can be used to:

- Aid in the prevention of soil erosion;
- Trap sediment from surface water runoff, as well as sediment-adsorbed contaminants;
- Capture nutrients and other potential contaminants;
- Reduce nutrient run-off by assimilation into the vegetation and/or by microbial activity (e.g., denitrification); and,
- Support the degradation of various pollutants.

As illustrated in Figure 1, a vegetative buffer consists of (i) surface vegetation, (ii) root zone, and (iii) a subsoil horizon.

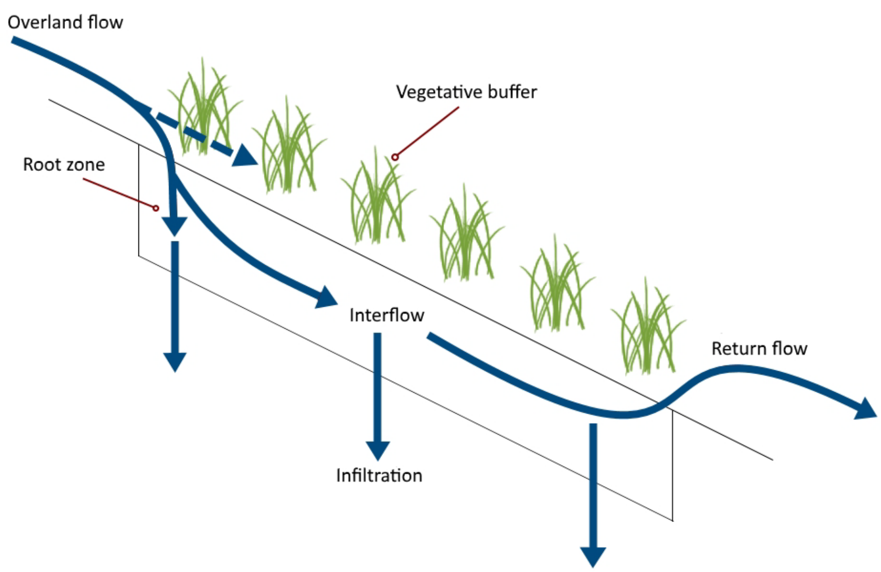

Figure 1: Cross-section of the patterns of water flow through hillside vegetative buffers. *Adapted from: Vegetative Filter Strips for Nonpoint Source Pollution Control in Agriculture Publication 8195 University of California Dept. of Agriculture and Natural Resources (2006)*

After encountering a vegetative buffer, the surface flow of water run-off first infiltrates in the root zone. Some infiltration occurs deeper into the subsoil, while the remainder becomes interflow within the soil horizon (Figure 1). The root zone allows for high infiltration rates because plant roots improve the surrounding soil structure and create macro-pores that promote infiltration.

Following infiltration, the shallow subsurface may become saturated. If the surface flow exceeds the infiltration capacity, overland flow occurs as indicated by the dashed line in Figure 1. Infiltration, followed by storage in the surface layer is the most important mechanism by which vegetative filter strips trap compounds that may exist in the surface run-off (e.g. pesticides, nutrients, soil particles, etc.). Compounds may remain trapped, degrade into breakdown products, or be metabolized by plants or microbes in the buffer zone.

Vegetative Buffers – A Positive Impact on Stewardship and Land Management

Soil Quality and Soil Stability

The root zone of a vegetative buffer is the primary area where absorption and chemical degradation takes place. The root zone can have a high concentration of soil micro-organisms and soil organic matter, both of which are critical in the retention and/or degradation of many pesticides. The vegetation within and surrounding these buffer strips not only provides organic matter, which improves soil quality, but is also a source/sink of soil carbon for micro-organisms, as well as nitrogen (if legumes are present). As a result, vegetative buffers reduce soil loss and protect productive topsoil. In addition, vegetative buffer strips adjacent to waterways can improve water quality by reducing run-off that could be a vector for contaminants, minimizing the risk of flooding that results from excess runoff, and avoiding erosion by stabilizing the soil on river banks (1-3).

Water Quality

In general, the vegetation present in vegetative buffers provides greater resistance to water flow. The reduction in the flow of water results in (i) increased infiltration, (ii) the trapping of sediments and associated pesticide residues, (iii) increased opportunity for assimilation of nutrient run-off by vegetation and microbial populations (1-3). Trapping of sediment is an important function. Increased sediment flow into waterways can be harmful to aquatic life due to increased biological demand (and consequently decreased available dissolved oxygen in the waterway) and can promote eutrophication of water bodies due to increased nutrient availability.

Wildlife Habitat

Vegetative filter strips and other land buffers play a critical role in maintaining and protecting biodiversity in agriculture-dominated landscapes by providing food, nesting, and habitat for wildlife (2, 3). For example, buffer areas can provide significant nesting habitat for grassland birds. They can also support a diverse plant community, supporting native pollinators and other insects through the creation of habitat and forage. Small mammals in agricultural landscapes use shrubby and herbaceous vegetative strips as escape covers. Furthermore, vegetative buffers can act as corridors through which wildlife can safely move from one habitat to another, promoting stable wildlife populations.

Types of Vegetative Buffers

There are two general types of vegetative buffers: permanent and temporary/flexible: (3, 30)

i. Permanent:

Certain areas or strips of land have permanent vegetation that has been established through planting or natural regeneration; these are referred to as permanent buffers. They reduce the loss of soil and nutrients via run-off water, reduce off-target pesticide flow and provide environmental benefits for wildlife habitats. There are a variety of permanent buffers:

a) Permanent Edge-of-Field Buffers such as:

- **Field borders** that are strips of permanent perennial vegetation that are established on the edges of crop fields. These borders (i) reduce the off-target movement of pesticides and nutrients which are present in the runoff water, (ii) trap the eroding soil containing adsorbed pesticides, and (iii) reduce the risk of pesticide drift by physically separating the spraying operation from adjacent lands that are not being sprayed.

- **Filter strips** that are located between crop fields and water bodies, with the intent of reducing runoffs. They consist of areas of grass and permanent vegetation. When combined with vegetative barriers, level spreaders or water bars, filter strips are usually more effective in the reduction of concentrated flow.

- **Riparian forest buffers** ('streamside management zones', 'forest buffers', 'riparian forests', and 'riparian management zones') are found adjacent to ponds, rivers, lakes, streams and wetlands, and consist of areas planted in trees and shrubs. Riparian buffers may be two or three zones running parallel to the water body. For intensively used cropland or pasture, two-zone buffers may be preferred. This two zone system consists of three to four rows of trees and shrubs closest to the water body, followed by grassy species chosen specifically for the site. For other conditions, such as highly erodible soils or gently sloping riverbanks, a three zone buffer is recommended. With this design, trees form zone one (adjacent to the waterbody and edge/bank), followed by a mixture of trees and shrubs to form zone two, with grasses planted in an area to form zone three.

- **Ecological buffers (Eco-buffers)** are a multi-function, multi-species dense planting design for field edge and riparian zones. These buffers are designed to mimic large natural buffers in a narrower space. Multiple rows of native trees and shrub species are interspersed in each row, including long- and short-lived species with a variety of growth rates and habits. High density (5000 plants/100 m compared to 350 plants/100 m in a traditional buffer) reduces the need for long-term weed control.

Field border

Filter strip

Riparian forest buffer

Eco-buffer (Photo from Reference 33)

b) Within-Field Buffers such as:

- **Grassed waterways** that are strategically constructed or naturally vegetated channels within an agricultural field. These waterways slow the flow of water, thereby preventing gully and rill (i.e. shallow channel) erosion, increase runoff water infiltration, and help trap pesticides and sediments.

- **Contour buffer strips** that alternate between perennial vegetation and cultivated strips. These strips help reduce the risk of gully erosion, concentrated flow and pesticide runoff by partitioning large cultivated areas into small strips.

- **Vegetative barriers** that have stiff stemmed, dense and tall perennial vegetation. By being placed parallel to each other and perpendicular to the slope, they help disperse concentrated flow and thus trap sediments better and have better rates of infiltration.

- **Wind buffers** ('windbreaks' or 'shelter-belts') that protect crops from intense and damaging winds and subsequent wind erosion of the topsoil. These buffers consist of single or multiple rows of trees and are sometimes planted along the edges of fields. By lowering the wind speed, these areas can help reduce pesticide drift. If placed perpendicular to the slope, they also help to reduce runoff. One variation of wind buffers are **herbaceous wind barriers** that usually consist of tall grasses that have been planted in thin rows, perpendicular to the general wind direction. These grasses reduce wind speed and intercept wind-borne nutrients and pesticides. Another variation, **cross wind trap strips,** reduce wind erosion but not wind speed. This also helps to intercept wind-borne sediments, nutrients and pesticides.

c) Constructed Wetlands:

While not typically considered buffers, constructed wetlands not only result in similar water quality benefits, but also provide additional benefits when combined with vegetative buffer areas. For example, low concentrations of pesticides can sometimes drain directly into streams via drainage tiles. Strategically located wetlands (e.g. at tile outlets) can be effective in degrading/sequestering pesticides and nutrients.

d) Saturated Buffers:

Similarly to a constructed wetland, saturated buffers exist where tile drainage output is delivered underground to the root zone of a vegetative buffer. The buffer stores the run-off and slowly releases it back to the natural draining as the moisture profile is reduced.

ii. Temporary (or Flexible) Buffers:

Sometimes, when permanent vegetative buffers have not been established or are inadequate for specific conditions, a portion of the crop or landscape can be earmarked, which is untreated and large enough to minimize the chances of spray drift, water runoff, and soil erosion. These areas are known as flexible buffers and their size and location are determined on an individual case-by-case basis.

In addition to considering permanent or flexible buffers, other measures should be considered to reduce the possibility of off-target pesticide movement by reducing spray drift, water runoff, and soil erosion. Examples of other measures include:

- Use of low-drift nozzles, drift retardants and shields
- Application of pesticides in the appropriate weather conditions:
    - avoid spraying when winds are variable to minimize unpredictable drifting;
    - avoid spraying when conditions are conducive to formation of a temperature inversion layer (e.g. completely calm or foggy weather), as pesticide droplets may move through this inversion layer of air
- Modification of use rate and/or pesticide incorporation
- Avoidance of spraying when soil is saturated
- Use of conservation tillage and cover crops to reduce soil erosion and water runoff

Design, Construction and Maintenance

In order to leverage the complete range of benefits offered by vegetative buffers and ensure their long-term effectiveness, a number of factors should be taken into account. A variety of field conditions such as the slope, soil roughness, infiltration capacity of the vegetated area, plant height, strip width (or available area), soil type and rainfall intensity will modulate the effectiveness of vegetative buffers. These factors should be considered when selecting the location and type of vegetative buffer system.

i. Site and location: (1-3, 30)

a) Site conditions should be designed in such a way so as to maximize interactions not only between overland flow through the buffer but also between shallow groundwater and the buffer.

b) Ideal locations for buffers include marginal and highly erodible land. They can also be placed at areas which receive a significant volume of runoff directly from fields, such as runoff points along streams and lakes.

c) Minimizing concentrated flow is one of the most important factors in designing and maintaining buffers. Ensuring that buffer edges have dense vegetation is an effective approach.

d) Dense vegetation affects the resistance to overland flow and thus is critical in maximizing the pollutant-trapping capacity of buffers.

e) In-field contour buffer strips and vegetative barriers manage sheet (i.e. overland) flow and infiltration very effectively.

f) In-field herbaceous wind-barriers and cross-wind traps are effective at managing wind erosion.

g) The width of the vegetative buffer is dependent upon the purpose of the buffer strip, whether it be sediment and nutrient retention, pesticide run-off, wildlife habitat, etc. For bank stability, a small buffer may be effective. For sediment removal, medium sized buffers are recommended. This category of vegetative buffers has been demonstrated to be effective at reducing pesticide run-off into waterbodies. Larger buffers are highly effective in minimizing sediment, nutrient and pesticide transport in water. For wildlife habitat protection and/or restoration, larger buffers may be required depending on the intended species.

h) Areas with a slope of less than 15% are recommended for vegetative buffers, as water run-off speed plays a role in buffer efficiency.

i) Depending on site conditions and the vegetation to the planted, the method used to prepare the vegetative buffer strip area for planting may vary. For certain conditions, such as planting a legume and grass mix, the site may be planted using no-till seeding equipment. However, in areas with extensive vegetative cover already in place, mechanical control and conditioning via tillage may be required. For areas where trees, shrubs, or other vegetation is planning, it is recommended to till the land where the buffer is being placed by discing, harrowing, and/or raking it, in order to prepare a good seedbed. Fertilizers, lime, compost, or gypsum can also be added before the actual planting. However, it is important to note that if tillage or other mechanical processes are used to condition to the area, early emergent cover crops and/or erosion control blankets should be considered to reduce the movement of soil and nutrients into the waterway.

j) Where possible, adjacent fields should be planted with rows running in a perpendicular direction to the vegetative buffer strip in order to minimize the flow and speed of surface run-off. This is particularly important during the year of establishment of the buffer.

ii. Planting mixture: (3, 30, 32, 33)

a) A combination of grasses (closest to cropped land), and trees and shrubs (closest to streams) is often the best combination for conservation buffers. Depending on local and site-specific considerations, an ecological buffer (eco-buffer) dense design may provide a good template.

b) Vegetation varieties that are native and are adapted to the local climate, site conditions and soil types are always preferred wherever available. Pollinator-attractive species can be used in buffer zones to provide feed and shelter for pollinators especially when adjacent to crops that require fruit pollination, such as fruits, canola, and other insect-pollinated crops.

c) Strong stemmed species are recommended when installing perennial grass buffers, as they form not only dense stands above ground, but also a deep root system below ground. The stands reduce runoff and increase infiltration. The root systems intercept subsurface flow, provide a habitat and source of carbon for micro-organisms that degrade pesticides, and facilitate denitrification.

d) Grasses and legumes planted at higher rates improve water quality, at moderate rates improve both water quality and wildlife habitat, and at lower rates provide optimal wildlife habitat.

e) Sturdy, tall perennial grasses are the most effective at trapping sediments. Native shrubs such as dogwood and willow are effective at improving bank stability.

iii. Maintenance: (1-3)

a) The land should be maintained to encourage shallow sheet flow and water infiltration. Areas that have developed channels and rills should be repaired and re-seeded.

b) Heavy equipment traffic on buffers should be minimized as this compact soils and creates ruts, which results in concentrated flow and reduced infiltration.

c) Care should be taken to avoid tilling and/or seeding (or planting the crop) too close to the buffer as steep-sided buffers are prone to degradation.

d) Buffers should be inspected after intense rain or runoff events to check for bare spots and other signs of erosion.

e) Excess sediment buildup (over 15 cm deep) should be removed and affected areas should be reseeded in order to maintain proper water flow and effectiveness of the buffer.

f) Livestock grazing near buffers should be kept to a minimum and only under optimum soil conditions as overgrazing leads to soil compactions, injured woody species, and water contamination. Consider fencing out livestock and providing an alternate watering source.

g) If improved wildlife habitats are the desired outcome of the vegetative buffer, prescribed fire and light discing practices may be used to maintain the native herbaceous community and retain bare ground required for small mammals and ground nesting birds. However, these practices should be utilized with care in semi-arid and arid regions in order to maintain soil health and to minimize erosion.

h) If unmanaged, the natural succession of vegetation tends to progress towards those plant species that dominate the local fauna (e.g. hardwood-based ecosystems in eastern Canada). As a result, early successional grass buffers must be periodically managed to maintain the intended plant community. Actively growing vegetation is crucial for better absorption and degradation of pesticides, as well as carbon supply for soil micro-organisms.

i) Mowing can be important for the effective functioning of buffers. For example, buffers can be mowed to a height of 12 to 30 cm to deter the growth of noxious weeds. Occasional harvest is also helpful to prevent nutrient buildup; however care should be taken to avoid mowing too short as it may limit the vegetation's ability to reduce flow during the non-growing season.

j) Care should be taken not to over-spray herbicides onto the buffer, which will impact the viability of the vegetation and reduce the effectiveness of the area in reducing run-off.

Vegetative Buffer Literature Review

The following section summarizes the key findings of select academic research on vegetative buffers/filter strips and (i) pesticides, (ii) sediments, and (iii) non-point source pollution, respectively. For each subsection, the relevant research papers from which these findings have been summarized can be found in Appendix A. A complete list of the publications and abstracts is found in Appendix C.

i. **VEGETATIVE BUFFERS AND PESTICIDES**

• **Summary and Key Findings**

a) Vegetative filter strips (VFS) have been shown to be effective in reducing pesticide run-off. For example, a variety of factors such as strip width (4), species present in the VFS zone (8) and compound properties modulate the effectiveness of the strips (15). Buffers has been shown to reduce the concentration of some pesticides, including neonicotinoids, in groundwater and footslope soil (e.g. 34).

b) The ability of vegetation itself to promote infiltration, adsorb pesticides and delay surface run-off also contributes to reducing run-off (12).

c) Vegetative filter strips that have grass cover only eventually change their cover composition due to the substitution of grass by broadleaf species. Six-meter wide strips have been shown to be highly effective in reducing herbicide run-off volume and concentration both during dry and wet years (12). According to the analysis of data from nearly 700 monitored sites in Germany, results indicate that riparian buffer strips of at least 5 m reduce pesticide run-off (5). A combined forest and grass buffer design provides effective watercourse protection against herbicide pollution, with 12 meter grass strips being highly efficient in decreasing flow (13). Overall, vegetative filter strips can reduce pesticide transfer to surface water by up to 90-98% (6).

d) Computational models such as the Vegetative Filter Strip Modeling System (VFSMOD-W) can predict pesticide, run-off, and sediment reduction but also evaluate the effectiveness of vegetative filter strips and the environmental conditions that may render them ineffective. (9,10,14,17,18,21)

- Studies have shown that the saturated hydraulic conductivity is the most important factor to predict infiltration and runoff [for both high and low loading rates (>75% and ~50% respectively)]. (10)

- Current research stresses the importance of considering hydrological processes, rather than the physical characteristics of the buffer, in order to make more accurate computational predictions of pesticide trapping efficiency. (14)

- Current computational models that calculate the efficiency of vegetative filter strips to remove non-point sources of contamination currently only take into account pollutant runoff and surface filtration functions. (25)
- Recent studies have shown that vertical preferential flow channels that can direct water beneath a vegetated buffer strip are an overlooked method for the movement of soluble contaminants into waterways. The authors suggest that buffer strip design can be used to minimize this risk through the use of plants with deep, fine roots to intercept soluble contaminant movement via preferential flow, or through the use of underground filters. (30)

ii. **VEGETATIVE BUFFERS AND SEDIMENTS**

• **Summary and Key Findings**

a) Slope and runoff volume are two critical factors that drive the export of sediments from fields (22, 23).

b) Vegetative buffers ranging from 3 to 9 m had greater than 90% sediment reduction rate (22).

c) Adopting dense vegetation buffers is an effective way to protect the environment and mitigate agricultural impacts (22).

d) The two major factors that influence the efficacy of best management practices for vegetated buffers on sediment trapping are buffer width and slope (23).

iii. **VEGETATIVE BUFFERS AND NONPOINT SOURCES**

• **Summary and Key Findings**

a) When designing riparian buffers, agricultural best management practices should take into account the uneven spatial distribution of potential sources of run-off, and environmental benefits (24). This will enable farmers and growers to more effectively reduce nutrient and sediment input to surface waters.

b) Important factors that dictate the removal efficiency of vegetation-filter strips on nonpoint source pollutants are amount of vegetation coverage, width of the strip and inflow concentration (28).

c) Buffers composed of solely trees rather than a mixture of grasses and trees have a relatively higher nitrogen and phosphorous removal efficiency (29).

d) Vegetation coverage ratio is a critical factor that needs to be taken into account when considering the efficiency of vegetative filter strips in removing non-point sources of contamination (26).

Provincial Regulations Regarding the Use of Vegetative Buffers in Pesticide Mitigation

Some provinces have separate regulations regarding the use of vegetative buffers to prevent run-off and improve water quality. Regulations may differ for own-use applications (e.g. farmer-use) as opposed to commercial applications (e.g. custom spraying) that are described in Table 1. Detailed regulations can be found in Appendix B.

Table 1: *Provincial Regulations Regarding the Use of VBs for Pesticide Application*

Province	Regulations for Growers	Regulations for Commercial Applicators
New Brunswick	No specific requirements other than the label statement (e.g. buffer zone).	No pesticide application within 12 m of surface water, with the exclusion of intermittent streams that are dry at the time of the application. If the label statement requires a larger setback, then the label setback must be followed.
Nova Scotia	No specific requirements other than the label statement (e.g. buffer zone), except in the case of an area designed as a protected water area. Specific regulations may apply to individual protected water areas.	
Prince Edward Island	A minimum distance of 15 m between a crop and a watercourse/wetland, with regulated row crops requiring at least 10 m of grassed headland (which can be within the buffer zone or beyond it). Fields with steeper slopes (i.e. > 5%) within 50 m of the upland boundary of the 10 m buffer and having no other mitigating management practices in place are required to have a 20 m vegetative filter strip. The slope of cultivated land cannot be greater 9% (applies to both row crops and vegetative filter strips) unless the farm has a farm management plan.	
Ontario	No specific requirements other than the label statement related to buffer zones. If the setback distance is not specified on the pesticide label, applicators must determine a suitable setback to protect the water body and adjacent riverbank from any material that may be harmful to fish, fish habitat or to endanger threatened fishes or freshwater mussels.	
Quebec	It is prohibited to apply pesticides for agricultural purposes • less than 3 m from any waterbody, including a ditch, where the total flow area is greater than 2 m^2 • less than 1 m from any watercourse, including a ditch, having a total flow area of 2 m^2 or less	

	Agricultural pesticides [other than *Bacillus thuringiensis* (Kurstaki variety)] must be applied more than 30 m from any waterbody or protected immovable (e.g. a business, a public beach, a municipal park, etc.) if the height of the application apparatus from the ground is less than 5 m, and more than 60 m away if the height of the apparatus from the ground is 5 m or more.
Alberta	There are several regulations for the application of specific pesticides within 30 m of a water body. See Appendix B for the relevant sections from the Code of Practice.
Saskatchewan	No specific requirements other than the label statement on buffer zones.
Manitoba	
British Columbia	

Use of Vegetative Buffers in Canada

Vegetative buffer are recognized as a Best Management Practice (BMP) under Growing Forward 2 (GF2) and their construction is (partially) funded under many of the provincial cost-share programs. Some of the BMPs relate directly to nutrient management from livestock facilities, while other BMPs relate to erosion control, reducing contaminant run-off or general water and soil quality, as described in Table 2.

Table 2: *Description of Cost-Share Funding for Vegetative Buffer Construction under GF2 Programs*

Province	Best Management Practice Funded	Description of Activity Funded
British Columbia	Water Quality, Air Quality, Soil Quality, and Biodiversity: Vegetative Buffer Planning	Services of a qualified consultant or EFP Program designate to produce a vegetative buffer plan (VBP) that includes a design layout, species list and maintenance protocols. Establishment of vegetative shelterbelts, buffers or hedgerows.
Alberta	Livestock Facility Runoff Control Funding Maximum	Constructed wetlands or vegetative filter systems, Engineering design and fees (if applicable), and Applicant's equipment use and in-kind labour (at set program rates).

Saskatchewan	Farm Stewardship Program: Water Flow and Erosion Control BMP Seeding High Risk Erodible Soils	Costs related to re-vegetation of waterways including seed, seedbed preparation, herbicide application and the seeding, when done in conjunction with water and erosion control structures and/or side sloping.
Manitoba	Ecological Goods and Services: Buffer and Grassed Waterway Establishment – air, soil and water quality	Establishment of perennial tame or native forages along waterways or natural runways. Eligible expenses include seed, seeding, weed control and materials required for grassed waterway construction.
Ontario	Water Protection Best Management Practices: A.7 Nutrient recovery from wastewater	Projects will focus on responsible water and nutrient resource management through use of nutrient recovery systems. Treatment trench systems, constructed wetlands or vegetated filter strip systems must be designed by a professional engineer
Quebec	Improve the agri-environmental management of manure from activities of beef enterprises.	The intervention carried out by the agricultural enterprise: Promotes the sound management of fertilizer materials; Reduces the impact of livestock on water and soil quality, etc. Projects may include: wintering pens, vegetative filtering strips, etc.
Newfoundland	Nutrient Management 3.3 Dewatering, recycling, and nutrient recovery systems for waste water from milk houses, fruit and vegetable washing, and greenhouses	Treatment trench systems, separate storage, transfer systems, constructed wetlands, or vegetated filter strips designed by professional engineer.
	Environmental Stewardship 4.2 Improved manure storage and handling.	Solid manure storage with separate runoff control or management system including constructed wetlands and vegetated filter strip.
New Brunswick	Vegetative buffers were not specifically identified as a BMP by these GF2 cost-share programs.	
Nova Scotia		
Prince Edward Island		

Summary

Vegetative buffers are one tool in the toolkit of land and crop management techniques available to growers to minimize environmental impact of agricultural operations on their property while simultaneously enhancing key ecological functions (e.g. biodiversity, habitat, etc.). The ability of buffers to trap sediment, reduce water speed, and promote infiltration helps to minimize the off-target movement of pesticides from spray drift, water runoff and soil erosion. These, combined with other management tools, including crop residues and/or cover crops, nutrient and pesticide management and precision technologies, contribute to the economic and environmental sustainability of farm production.

In addition to minimizing off-target pesticide movement, other potential benefits of well-designed and maintained buffers include:

- reduced soil erosion of topsoil and stabilization of riverbanks,
- improved water quality due to reduced sediment, nutrient loads and other potential contaminants, including pathogens, and;
- increased biodiversity of wildlife species, plants, and pollinators.

As outlined in the literature survey, the value of vegetative buffers as a tool to mitigate surface runoff has been demonstrated. Permanent buffer strips have been found to significantly reduce the movement of certain pesticides and compounds into waterways. The size and location of vegetative buffers depends on site-specific conditions (e.g. greater widths are required with increasing slope, different soil structure, etc.), as these factors impact the ability of the buffer to increase the opportunity for adsorption, adherence, trapping, degradation, and/or assimilation of sediment or contaminants

Current models of buffer systems include the impact of the physical characteristic of the buffer (soil type, width, etc.) and its interaction with surface run-off and in filtration water. More accuracy will be gained with greater understanding of the complex hydrologic processes that impact buffer efficiency far below the soil-line as well. Developing these advanced models may require more research into the range of hydrologic processes that can transport various types of contaminants into surface waters.

Appendix A - References

- **Literature cited (Introduction and Design, Construction & Maintenance)**

1. Grismer, M. E., O'Geen, A. T., and Lewis. D. (2006). "Vegetative Filter Strips for Nonpoint Source Pollution Control in Agriculture" ANR publication 8195

2. Helmers, Matthew J. Isenhart, Thomas M. Dosskey, Michael G. Dabney, Seth M. and Strock, Jeffrey S (2008). "Buffers and Vegetative Filter Strips" Agricultural and Biosystems Engineering Publications. 298.

3. The Value of Buffers for Pesticide Stewardship and Much More (2013). Syngenta Canada

- **Literature cited (Vegetative Buffers and Pesticides)**

4. Bereswill, R., M. Streloke and R. Schulz (2014). "Risk mitigation measures for diffuse pesticide entry into aquatic ecosystems: proposal of a guide to identify appropriate measures on a catchment scale." Integr Environ Assess Manag 10(2): 286-298.

5. Bunzel, K., M. Liess and M. Kattwinkel (2014). "Landscape parameters driving aquatic pesticide exposure and effects." Environ Pollut 186: 90-97.

6. Cardinali, A., S. Otto and G. Zanin (2013). "Herbicides runoff in vegetative filter strips: evaluation and validation of a recent rainfall return period model." Int J Environ Anal Chem 93(15): 1628-1637.

7. Kapil Arora, Steven K. Mickelson, Matthew J. Helmers, and James L. Baker. Review of Pesticide Retention Processes Occurring in Buffer Strips Receiving Agricultural Runoff. Journal of the American Water Resources Association 46(3):618-647.

8. Krutz, L. J., S. A. Senseman, R. M. Zablotowicz and M. A. Matocha (2005). "Reducing herbicide runoff from agricultural fields with vegetative filter strips: A review." Weed Sci 53(3): 353-367.

9. Munoz-Carpena, R., G. A. Fox and G. J. Sabbagh (2010). "Parameter importance and uncertainty in predicting runoff pesticide reduction with filter strips." J Environ Qual 39(2): 630-641.

10. Munoz-Carpena, R., A. Ritter, G. A. Fox and O. Perez-Ovilla (2015). "Does mechanistic modeling of filter strip pesticide mass balance and degradation processes affect environmental exposure assessments?" Chemosphere 139: 410-421.

11. Otto, S., A. Cardinali, E. Marotta, C. Paradisi and G. Zanin (2012). "Effect of vegetative filter strips on herbicide runoff under various types of rainfall." Chemosphere 88(1): 113-119.

12. Otto, S., M. Vianello, A. Infantino, G. Zanin and A. Di Guardo (2008). "Effect of a full-grown vegetative filter strip on herbicide runoff: maintaining of filter capacity over time." Chemosphere 71(1): 74-82.

13. Patzold, S., C. Klein and G. W. Brummer (2007). "Run-off transport of herbicides during natural and simulated rainfall and its reduction by vegetated filter strips." Soil Use Manag 23(3): 294-305.

14. Poletika, N. N., P. N. Coody, G. A. Fox, G. J. Sabbagh, S. C. Dolder and J. White (2009). "Chlorpyrifos and atrazine removal from runoff by vegetated filter strips: experiments and predictive modeling." J Environ Qual 38(3): 1042-1052.

15. Reichenberger, S., M. Bach, A. Skitschak and H. G. Frede (2007). "Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review." Sci Total Environ 384(1-3): 1-35.

16. Sabbagh, G. J., G. A. Fox, A. Kamanzi, B. Roepke and J. Z. Tang (2009). "Effectiveness of vegetative filter strips in reducing pesticide loading: quantifying pesticide trapping efficiency." J Environ Qual 38(2): 762-771.

17. Sabbagh, G. J., G. A. Fox, R. Munoz-Carpena and M. F. Lenz (2010). "Revised framework for pesticide aquatic environmental exposure assessment that accounts for vegetative filter strips." Environ Sci Technol 44(10): 3839-3845.

18. Sabbagh, G. J., R. Munoz-Carpena and G. A. Fox (2013). "Distinct influence of filter strips on acute and chronic pesticide aquatic environmental exposure assessments across U.S. EPA scenarios." Chemosphere 90(2): 195-202.

19. Stehle, S., D. Elsaesser, C. Gregoire, G. Imfeld, E. Niehaus, E. Passeport, S. Payraudeau, R. B. Schafer, J. Tournebize and R. Schulz (2011). "Pesticide risk mitigation by vegetated treatment systems: a meta-analysis." J Environ Qual 40(4): 1068-1080.

20. Tang, X., B. Zhu and H. Katou (2012). "A review of rapid transport of pesticides from sloping farmland to surface waters: processes and mitigation strategies." J Environ Sci (China) 24(3): 351-361.

21. Winchell, M. F., R. L. Jones and T. L. Estes (2011). Comparison of models for estimating the removal of pesticides by vegetated filter strips. Pesticide Mitigation Strategies for Surface Water Quality, American Chemical Society. 1075: 273-286.

- **Literature cited (Vegetative Buffers and Sediment)**

22. Campo-Bescos, M. A., R. Munoz-Carpena, G. A. Kiker, B. W. Bodah and J. L. Ullman (2015). "Watering or buffering? Runoff and sediment pollution control from furrow irrigated fields in arid environments." Agric Ecosyst Environ 205: 90-101.

23. Liu, X., X. Zhang and M. Zhang (2008). "Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis." J Environ Qual 37(5): 1667-1674.

- **Literature cited (Vegetative Buffers and Non-Point Sources)**

24. Diebel, M. W., J. T. Maxted, P. J. Nowak and M. J. Vander Zanden (2008). "Landscape planning for agricultural nonpoint source pollution reduction I: a geographical allocation framework." Environ Manage 42(5): 789-802.

25. Dosskey, M. G. (2001). "Toward quantifying water pollution abatement in response to installing buffers on crop land." Environ Manage 28(5): 577-598.

26. Shin, J. and K. Gil (2015). "Determination of removal efficiency using vegetative filter strips based on various efficiency evaluation methods." Environ Earth Sci 73(10): 6437-6444.

27. Schulz, R. (2004). "Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution: a review." J Environ Qual 33(2): 419-448.

28. Yang, F., Y. Yang, H. Li and M. Cao (2015). "Removal efficiencies of vegetation-specific filter strips on nonpoint source pollutants." Ecol Eng 82: 145-158.

29. Zhang, X., X. Liu, M. Zhang, R. A. Dahlgren and M. Eitzel (2010). "A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution." J Environ Qual 39(1): 76-84.

Other Literature Cited

30. Agriculture and Agri-Food Canada (2015, accessed October 20, 2017) Shelterbelt planning and establishment - Riparian buffers.

31. Allaire SE, Sylvain C, Lange SF, Thériault G, and P Lafrance (2015) Potential efficiency of riparian vegetated buffer strips in intercepting soluble compounds in the presence of subsurface preferential flows. PLoS ONE 10(7): e0131840.

32. Agriculture and Agri-Food Canada (2015) Willow Riparian Buffers. AAFC No. 12433E.

33. Agriculture and Agri-Food Canada (2017) Eco-Buffers: An Alternative Agroforestry Design. AAFC No. 12694E.

34. Hladik. ML, Bradbury S, Schulte LA, Helmers M, Witte C, Kolpin DW, Garrett JD and M Harris (2017) Neonicotinoid insecticide removal by prairie strips in row-cropped watersheds with historical seed coating use. Agriculture, Ecosystems and Environment 241: 160-167.

Appendix B - Provincial Regulations Regarding Buffers

<table>
<tr><th>Region</th><th>Regulations for Growers</th><th>Regulations for Commercial Applicators</th></tr>
<tr><td>New Brunswick</td><td>No specific requirements other than the label statement (e.g. buffer zone).</td><td>Pesticide Control Act (paraphrased):
No pesticide application be conducted within 12 m of:
- Occupied habitation.
- Property boundaries where there is the possibility of drift onto land adjacent to the treatment area.
- Surface water, with the exclusion of intermittent streams that are dry at the time of the application. Should a product label specify a greater aquatic setback, then the label setbacks must be maintained.</td></tr>
<tr><td>Nova Scotia</td><td colspan="2">Environment Act Section 21: Protected water area
“No person shall apply a pesticide within a protected water area designated under Section 106 of the [Nova Scotia Environment] Act unless the person complies with any regulations regarding the use of pesticides within the protected water area.”</td></tr>
<tr><td>Prince Edward Island</td><td colspan="2">Environmental Protection Act Watercourse and Wetland Protection (paraphrased):
No person shall, without a license or a Buffer Zone Activity Permit, and other than in accordance with the conditions thereof,
• alter or disturb the ground or soil within 15 m of a watercourse boundary or a wetland boundary, or cause or permit the alteration or disturbance of the ground or soil, therein, in any manner.
• engage in or cause or permit the engaging in spraying or applying pesticides in any manner within 15 m of a watercourse boundary or a wetland boundary.

No person shall, without a grass headland variance or grass headland exemption, and other than in accordance with the terms and conditions thereof, cultivate a row crop within 200 m of any watercourse boundary or wetland boundary unless every row that ends within 200 m of any watercourse boundary or wetland boundary ends at
(a) a grass headland
(b) a buffer zone.

“Grass headland” means an area of live perennial grass
(a) which was planted prior to the calendar year in which the row crop was planted;</td></tr>
</table>

	(b) which is at least 10 m in width, measured commencing at the end of each row and continuing in the same direction as each row; and (c) no part of which is contained within a buffer zone.
Ontario	No specific requirements other than the label statement related to buffer zones.
Saskatchewan	
Manitoba	
British Columbia	
British Columbia	Pesticides Code of Practice, Section 30: “It is prohibited to apply pesticides for agricultural purposes (1) less than 3 m from a watercourse, body of water or ditch where the total flow area (average width multiplied by average height) of the part of the watercourse or ditch is greater than 2 m^2; the relative distance from a ditch is measured from its edgeline; and (2) less than 1 m from a watercourse, including an intermittent watercourse, or a ditch having a total flow area of 2 m^2 or less for the part of the watercourse or ditch; the relative distance from a watercourse is measured from the natural high-water mark of the watercourse as defined in the policy referred to in the second paragraph of section 1 and the relative distance from a ditch is measured from its edgeline. Pesticides other than Bacillus thuringiensis (Kurstaki variety) applied for agricultural purposes and in a non-forest environment must be applied more than 30 m from a watercourse or body of water if the height of application is less than 5 m from the ground, and more than 60 m from a watercourse or body of water if the height of application in 5 m or more from the ground. For the purposes of the first paragraph, the watercourses referred to in “watercourse or body of water” are the parts of a watercourse wider than 4 m; that width is measured from the natural high-water mark of the watercourse as defined in the policy referred to in the second paragraph of section 1. For watercourses whose width is less than 4 m, the prohibition set out in section 30 continues to apply.”
Alberta	Environmental Code of Practice for Pesticides Section 16: Pesticide Application Within 30 Horizontal Metres of an Open Body of Water **16(1)** In this section “deposit” means depositing an amount that results in visible effects on vegetation or an amount that is likely to cause an adverse effect. **(2)** All applications must be conducted or supervised by (a) the holder of a certificate of qualification for pesticide application, or (b) the holder of a certificate recognized by the Director. **(5)** Applications must not be made within 250 m upstream of any surface water intake of a waterworks system. **(6)** Aerial applications of pesticides to land must not be conducted while flying directly over an open body of water. **Herbicide Applications - General** **(7)** Herbicides must not be deposited within 30 horizontal m of an open

body of water unless the herbicide application is conducted by ground application equipment only.

(8) Herbicides must not be deposited on areas that have slumped, been washed out or are subject to soil erosion into the water body.

(9) Unless otherwise specified in the manufacturer's product label, applicators may apply the herbicides listed in Table 1 provided that

(a) herbicides are not deposited closer than 1 horizontal metre from an open body of water;

(b) applications are conducted for

(i) the control of herbaceous plants classified as weeds named under the *Weed Control Act*; or

(ii) control of woody plants less than 1.5 metres in height, to areas where the woody plants interfere with forest generation or the safe operation, functioning, or maintenance of man-made structures such as dams, canals, drainage ditches, roads, industrial facilities, or utility or pipeline rights-of-way;

(c) applications are made selectively using

(i) a backpack sprayer,

(ii) a pump-sprayer,

(iii) a hand-gun sprayer, or

(iv) an application method that targets individual plants; and

(d) no more than 10 percent of any 100 square metres in the zone 1 – 5 metres from an open body of water receives treatment in any calendar year.

Table 1

- aminopyralid (when used up to a maximum application rate of 0.12 kg active ingredient per hectare)
- chlorsulfuron
- clopyralid
- glyphosate
- metsulfuron-methyl (when used up to a maximum application rate of 0.09 kg active ingredient per hectare)
- triclopyr (when used up to a maximum application rate of 1.92 kg active ingredient per hectare)

(10) Unless otherwise specified in the manufacturer's product label, applicators may apply the herbicides listed in Table 1 or Table 2 provided that

(a) herbicides in Table 2 are not deposited closer than 5 horizontal metres from an open body of water;

(b) applications are conducted for:

(i) the control of herbaceous plants classified as weeds named under the *Weed Control Act;* or

(ii) the control of woody plants to areas where the woody plants interfere with forest regeneration or the safe operation, functioning, or maintenance of man-made structures such as dams, canals, drainage ditches, roads, industrial facilities, or utility or pipeline rights-of-way; and

(c) applications are made selectively using a backpack sprayer, a pumpsprayer, a hand-gun sprayer, a boom or boomless sprayer, or an application method that targets individual plants;

	(d) no more than 30 percent of any 100 square metres in the zone 5-30 metres from an open body of water receives treatment in any calendar year. **Table 2** • 2,4-D (when used up to a maximum application rate of 1.4 kg active ingredient per hectare). • aminopyralid (when used up to a maximum application rate of 0.12 kg active ingredient per hectare) • dicamba (when used up to a maximum application rate of 1.2 kg active ingredient per hectare) • dichlorprop (when used up to a maximum application rate of 1.2 kg active ingredient per hectare) • MCPA (when used up to a maximum application rate of 0.675 kg active ingredient per hectare) • triclopyr **(11)** Unless otherwise specified in the manufacturer's product label, applicators may apply herbicides for specific vegetation management situations as follows: (a) **Purple Loosestrife** (*Lythrum salicaria)* may be treated with glyphosate or triclopyr, applied selectively by backpack or handpump sprayer to purple loosestrife growing on dry land provided that: (i) no herbicide is deposited closer than 1 horizontal metre from standing water; and (ii) no more than 10 percent of any 100 square metres of land closer than 1 metre from an open body of water receives treatment in any calendar year. **Insecticide Application - General** **(13)** Unless otherwise specified in the manufacturer's product label, insecticides listed in Table 3 may be deposited up to the bed and shore of an open body of water provided the insecticide does not enter into or onto an open body of water. **Table 3** • *Bacillus thuringiensis*, • insecticidal soap, • insecticides or insect growth regulators applied by direct injection, banding, or basal spray. **(14)** Insecticides may be used for structural pest control purposes on the interior and the exterior of buildings located up to the bed and shore of an open body of water in accordance with label directions.
Federal Regulations	Setback Distances for Water Bodies: "It is an offence under the federal *Fisheries Act* to introduce into water any material that may be harmful to fish or fish habitat, and under the *Species at Risk Act*, to impact endangered or threatened fishes and fresh water mussels. To protect these waters, applicators must determine a suitable setback distance between the area to be protected and the area where pesticide treatments are planned (if the setback distance is not specified on the pesticide label). The protected area includes the water body as well

	as adjacent riparian (riverbank) areas that contribute to fish food and habitat.”

Appendix C - Summaries of Relevant Literature

Update on Available Literature on the Effectiveness of Vegetative Filter Strips (VFS) and Pesticide Mitigation

An updated literature search was conducted to aid in the development of the vegetative buffers as part of a stewardship program. The search was focused on the term vegetative filter strip (VFS) as well as VFS co-occurring (and/or) with the words pesticides, effectiveness, design, and/or run-off. Prior published literature reviews were included as were several studies focused solely on modeling. Titles and abstracts of studies evaluating the effectiveness of vegetative filter strips in agricultural settings are listed below. These studies were conducted at plot, edge of field or catchment scale. Additionally, four studies were included that evaluated the effectiveness of different landscape models at predicting expected run-off reductions from VFS. In the VFS effectiveness studies, the primary outcome measures were percent reduction in load and percent reduction in concentration of sediment, nutrient and/or pesticide. The studies varied in the number of input parameters they evaluated. They included: VFS width, slope, soil type, drainage area ratio, VFS location, run-off volume, and VFS species type. The four modeling studies compared several different landscape models including PRZM/EXAMS, VFSMOD, APEX, PRZ-BUFF, and REMM. The primary outcome evaluated in these studies was the accuracy with which these models could predict real run-off reductions from VFS.

From the information available in the published literature, the following generalizations can be drawn on the effectiveness of VFS. VFS are an effective best management practice (BMP) for mitigating agricultural non-point source run-off and protecting aquatic ecosystems. Their effectiveness is influenced by many factors. Most notably, VFS are more effective at trapping sediment and sediment bound constituents than they are at trapping soluble ones. In fact pesticides with a high K_{oc} (strongly sorbed to soil particle) can be effectively trapped at rates between 53 – 100%. While buffer width (also; length, size, area) is highly correlated to percent trapping effectiveness, the studies show that 5 m (~15 ft) is an effective width where trapping efficiencies are practical. Increasing VFS width beyond 5 m gives diminishing returns to effectiveness (beyond 75%) when considering pesticides that are highly sorbed to sediment.

Models are important to landscape planners and regulators who would like to determine where best management practices can be implemented across widely varying topographies and use regions. It is important to use a model that can accurately predict run-off reductions as a result of the proper placement of a BMP. It needs to take into account the many different input parameters like site characteristics and weather. Of the models discussed in the studies, VFMOD most closely predicts the actual data in the studies it was compared to (within 10%). Although pesticide regulators in Canada (i.e. Health Canada’s Pest Management Regulatory Agency) currently does not model the effect of vegetative buffers on aquatic exposure, models including VFSMOD are available and can work in tandem with approved Tier 2 models (e.g., PRZM/EXAMS).

In summary, a review of these studies indicates that VFS with a minimum width of 5 m (~15ft) is efficacious for run-off reduction. VFS are more efficient for certain types of run-off like sediment and pesticides that are highly sorbed to sediment with efficiencies in the range of 53 to 100%. It is important to select a model that can accurately predict run-off reductions across variable landscapes since run-off studies cannot be conducted for all scenarios in agriculture.

Following is the list of relevant citations on the impact of vegetative buffers as a mitigation tool for aquatic exposure of pesticides:

Bereswill, R., M. Streloke and R. Schulz (2014). "Risk mitigation measures for diffuse pesticide entry into aquatic ecosystems: proposal of a guide to identify appropriate measures on a catchment scale." Integr Environ Assess Manag 10(2): 286-298.

A concise compilation of the appropriate run-off reduction measures for users (that are primarily farmers but also, e.g., regulators and farm extension services) and a guide for practically identifying these measures at the catchment scale was proposed. The proposed guide focused on the most important diffuse entry pathways (spray drift and runoff). Based on a survey of exposure-relevant landscape parameters (i.e., the riparian buffer strip width, riparian vegetation type, density of ground vegetation cover, coverage of the water body with aquatic macrophytes, field slope, and existence of concentrated flow paths), a set of measures focusing on the specific situation of run-off to a water body catchment can be identified. The user can then choose measures to implement, assisted by evaluations of their efficiency in reducing pesticide entry, feasibility, and expected acceptability to farmers. Currently, 12 landscape-related measures and 6 application-related measures are included.

Bunzel, K., M. Liess and M. Kattwinkel (2014). "Landscape parameters driving aquatic pesticide exposure and effects." Environ Pollut 186: 90-97.

This study evaluated the potential effects of diffuse and point sources of pesticide run-off using macro-invertebrate monitoring data from 663 sites in central Germany. Authors investigated forested upstream reaches and structural quality as landscape parameters potentially impacting run-off of pesticides. Results indicate that forested upstream reaches and riparian buffer strips at least 5 m in width can reduce pesticide run-off. Authors developed a screening approach that allows an initial, cost-effective identification of sites of concern.

Campo-Bescos, M. A., R. Munoz-Carpena, G. A. Kiker, B. W. Bodah and J. L. Ullman (2015). "Watering or buffering? Runoff and sediment pollution control from furrow irrigated fields in arid environments." Agric Ecosyst Environ 205: 90-101.

Changes in irrigation systems can represent an economic alternative to reduce surface runoff impacts. At the same time the use of vegetative filter strips (VFS) can have a positive impact on the ecological health of rural landscapes by reducing erosion, improving water quality, increasing biodiversity, and expanding wildlife habitat. The goal of this paper is, using a combination of field data and mechanistic modeling results, to evaluate and compare the spatial effectiveness of improvements in irrigation systems and introduction of VFS to reduce surface runoff in the semi-arid/arid furrow irrigation agro-ecosystem that exceeds current regulatory limits. Five main factor interactions were studied: four soil textures, two field slopes, three irrigation systems (IS), six filter vegetation types, and ten filter lengths. Slope and runoff volume were identified as the two main drivers of sediment export from furrows. Shifting from current IS to less water consumptive irrigation practices reduce runoff in addition to sediment delivery to comply with environmental regulations. The implementation of 3–9 m vegetative buffers on experimental parcels were found to mitigate sediment delivery (greater than 90% sediment reduction) on tail drainage ditches but had limited effect in the reduction of runoff flow that can transport other dissolved pollutants. These findings were insensitive to filter vegetation type. Thus, introduction of improved IS is desirable while VFS may be targeted to specific hot spots within the irrigation district. This study shows that the adoption of dense vegetation buffers in vulnerable semi-arid irrigated regions can be effective to mitigate agricultural impacts and provide environmental protection.

Diebel, M. W., J. T. Maxted, P. J. Nowak and M. J. Vander Zanden (2008). "Landscape planning for agricultural nonpoint source pollution reduction I: a geographical allocation framework." Environ Manage 42(5): 789-802.

At local scales, agricultural best management practices (BMPs) have been shown to be effective at reducing nutrient and sediment inputs to surface waters. However, these effects have rarely been found to act in concert to produce measurable, broad-scale improvements in water quality. We investigated potential causes for this failure through an effort to develop recommendations for the use of riparian buffers in addressing nonpoint source pollution in Wisconsin. They used frequency distributions of phosphorus run-off at two spatial scales (watershed and field), along with typical stream phosphorus (P) concentration variability, to simulate benefit/cost curves for four approaches to geographically allocating conservation effort. The approaches differ in two ways: (1) whether effort is aggregated within certain watersheds or distributed without regard to watershed boundaries (dispersed), and (2) whether effort is targeted toward the fields most vulnerable to P run-off or is distributed randomly. In realistic implementation scenarios, the aggregated and targeted approach most efficiently improves water quality. For example, with effort on only 10% of a model landscape, 26% of the total P load is retained and 25% of watersheds significantly improve. Results indicate that agricultural conservation can be more efficient if it accounts for the uneven spatial distribution of potential sources of run-off and the cumulative aspects of environmental benefits.

Dosskey, M. G. (2001). "Toward quantifying water pollution abatement in response to installing buffers on crop land." Environ Manage 28(5): 577-598.

In this publication the scientific research literature was reviewed (i) for evidence of how much reduction in nonpoint source pollution can be achieved by installing buffers on crop land, (ii) to summarize important factors that can affect this response, and (iii) to identify remaining major information gaps that limit the ability to make probable estimates. This review was intended to clarify the current scientific foundation of the USDA and similar buffer programs designed in part for water pollution abatement and to highlight important research needs. At this time, research reports are lacking that quantify a change in pollutant amounts (concentration and/or load) in streams or lakes in response to converting portions of cropped land to buffers. Most evidence that such a change should occur is indirect, coming from site-scale studies of individual functions of buffers that act to retain pollutants from runoff: (1) reduce surface runoff from fields, (2) filter surface runoff from fields, (3) filter groundwater runoff from fields, (4) reduce bank erosion, and (5) filter stream water. The term filter is used here to encompass the range of specific processes that act to reduce pollutant amounts in runoff flow. A consensus of experimental research on functions of buffers clearly shows that they can substantially limit sediment runoff from fields, retain sediment and sediment-bound pollutants from surface runoff, and remove nitrate N from groundwater runoff. Less certain is the magnitude of these functions compared to the cultivated crop condition that buffers would replace within the context of buffer installation programs. Other evidence suggests that buffer installation can substantially reduce bank erosion sources of sediment under certain circumstances. Studies have yet to address the degree to which buffer installation can enhance channel processes that remove pollutants from stream flow. Mathematical models offer an alternative way to develop estimates for water quality changes in response to buffer installation. Numerous site conditions and buffer design factors have been identified that can determine the magnitude of each buffer function. Accurate models must be able to account for and integrate these functions and factors over whole watersheds. Currently, only pollutant runoff and surface filtration functions have been modeled to this extent. Capability is increasing as research data is produced, models become more comprehensive, and new techniques provide means to describe variable conditions across watersheds. A great deal of professional judgment is still required to extrapolate current knowledge of buffer functions into broadly accurate estimates of water pollution abatement in response to buffer installation on crop land. Much important research remains to be done to improve this capability. The greatest need is to produce direct quantitative evidence of this response. Such data would confirm the hypothesis and enable direct testing of watershed-scale prediction models as they become available. Further study of individual pollution control functions is also needed, particularly to generate comparative evidence for how much they can be manipulated through buffer installation and management.

Hladik. ML, Bradbury S, Schulte LA, Helmers M, Witte C, Kolpin DW, Garrett JD and M Harris (2017) Neonicotinoid insecticide removal by prairie strips in row-cropped watersheds with historical seed coating use. Agriculture, Ecosystems and Environment 241: 160-167.

This study compared neonicotinoid concentrations in groundwater, surface water runoff and in footslope soil in sites with prairie buffer strips and without. Neonicotinoid-treated seeds had been used in the study sites between 2008-2013, but had been discontinued for 2 years prior to the study in 2015-2016. Sites with buffer strips of prairie species comprising 10% of an agricultural catchment had lower concentrations of neonicotinoids in groundwater, as these sites with prairie buffer strips had a mean concentration of 11 ng/L versus 20 ng/L with no prairie strip. This result suggests that there was less offsite transport of pesticides via groundwater due to prairie buffer strips. Concentrations in soil were also lower, as sites with prairie buffer strips had neonicotinoid concentrations of <1 ng/g versus 6 ng/g without a prairie buffer strip. In surface run-off water, neonicotinoids were less frequently detected in sites with prairie buffer strips than control sites, but there was no significant difference in concentration of neonicotinoid in surface run-off water when averaged over all sites. Neonicotinoids were not detected the root, leaf or flower tissues of the plants in the prairie buffer strips, suggesting that two years after the discontinuation of neonicotinoid treatments at these sites, pollinators and other species were not being exposed to neonicotinoids through these buffer plants. These study results demonstrates that buffer strips are a potential tool to mitigate the off-site transport of neonicotinoids.

Liu, X., X. Zhang and M. Zhang (2008). "Major factors influencing the efficacy of vegetated buffers on sediment trapping: a review and analysis." J Environ Qual 37(5): 1667-1674.

This literature review of vegetated buffers, including vegetative filter strips, riparian buffers, and grassed waterways, are best management practices (BMPs) installed in many areas to filter sediments from tail waters, and deter sediment transport to water bodies. Along with reducing sediment transport, the filters also help trap sediment bound nutrients and pesticides. The objectives of this study were: (i) to review vegetative buffer efficacy on sediment trapping, and (ii) to develop statistical models to investigate the major factors influencing sediment trapping. A range of sediment trapping efficacies was found in a review of over 80 representative BMP experiments. A synthesis of the literature regarding the effects of vegetated buffers on sediment trapping is needed. The meta-analysis results based on the limited data showed that buffer width and slope are two major factors influencing BMPs efficacy of vegetated buffers on sediment trapping. Regardless of the area ratio of buffer to agricultural field, a 10 m buffer and a 9% slope optimized the sediment trapping capability of vegetated buffers.

Munoz-Carpena, R., G. A. Fox and G. J. Sabbagh (2010). "Parameter importance and uncertainty in predicting runoff pesticide reduction with filter strips." J Environ Qual 39(2): 630-641.

Vegetative filter strips (VFS) are an environmental management tool used to reduce sediment and pesticide transport from surface runoff. Numerical models of VFS such as the Vegetative Filter Strip Modeling System (VFSMOD-W) are capable of predicting runoff, sediment, and pesticide reduction and can be useful tools to understand the effectiveness of VFS and environmental conditions under which they may be ineffective. However, as part of the modeling process, it is critical to identify input factor importance and quantify uncertainty in predicted runoff, sediment, and pesticide reductions. This research used state-of-the-art global sensitivity and uncertainty analysis tools, a screening method (Morris) and a variance-based method (extended Fourier Analysis Sensitivity Test), to evaluate VFSMOD-W under a range of field scenarios. The three VFS studies analyzed were conducted on silty clay loam and silt loam soils under uniform, sheet flow conditions and included atrazine, chlorpyrifos, cyanazine, metolachlor, pendimethalin, and terbuthylazine data. Saturated hydraulic conductivity was the most important input factor for predicting infiltration and runoff, explaining >75% of the total output variance for studies with smaller hydraulic loading rates (approximately 100-150 mm equivalent depths) and approximately 50% for the higher loading rate (approximately 280-mm equivalent depth). Important input factors for predicting sedimentation included hydraulic conductivity, average particle size, and the filter's Manning's roughness coefficient. Input factor importance for pesticide trapping was controlled by infiltration and, therefore, hydraulic conductivity. Global uncertainty analyses suggested a wide range of reductions for runoff (95% confidence intervals of 7-93%), sediment (84-100%), and pesticide (43-100%). Pesticide trapping probability distributions fell between runoff and sediment reduction distributions as a function of the pesticides' sorption. Seemingly equivalent VFS exhibited unique and complex trapping responses dependent on the hydraulic and sediment loading rates, and therefore, process-based modeling of VFS is required.

Munoz-Carpena, R., A. Ritter, G. A. Fox and O. Perez-Ovilla (2015). "Does mechanistic modeling of filter strip pesticide mass balance and degradation processes affect environmental exposure assessments?" Chemosphere 139: 410-421.

Vegetative filter strips (VFS) are a widely adopted practice for limiting pesticide transport from adjacent fields to receiving water bodies. The efficacy of VFS depends on site-specific input factors. To elucidate the complex and non-linear relationships among these factors requires a process-based modeling framework. Previous research proposed linking existing higher-tier environmental exposure models with a well-tested VFS model (VFSMOD). However, the framework assumed pesticide mass stored in the VFS was not available for transport in subsequent storm events. A new pesticide mass balance component was developed to estimate surface pesticide residue trapped in the VFS and its degradation between consecutive runoff events. The influence and necessity of the updated framework on acute and chronic estimated environmental concentrations (EECs) and percent reductions in EECs were investigated across three, 30-year U.S. EPA scenarios: Illinois corn, California tomato, and Oregon wheat. The updated framework with degradation predicted higher EECs than the existing framework without degradation for scenarios with greater sediment transport, longer VFS lengths, and highly sorbing and persistent pesticides. Global sensitivity analysis (GSA) assessed the relative importance of mass balance and degradation processes in the context of other input factors like VFS length (VL), organic-carbon sorption coefficient (Koc), and soil and water half-lives. Considering VFS pesticide residue and degradation was not important if single, large runoff events controlled transport, as is typical for higher percentiles considered in exposure assessments. Degradation processes become more important when considering percent reductions in acute or chronic EECs, especially under scenarios with lower pesticide losses.

Poletika, N. N., P. N. Coody, G. A. Fox, G. J. Sabbagh, S. C. Dolder and J. White (2009). "Chlorpyrifos and atrazine removal from runoff by vegetated filter strips: experiments and predictive modeling." <u>J Environ Qual</u> 38(3): 1042-1052.

Runoff volume and flow concentration are hydrological factors that limit effectiveness of vegetated filter strips (VFS) in removing pesticides from surface runoff. Empirical equations that predict VFS pesticide effectiveness based solely on physical characteristics are insufficient on the event scale because they do not completely account for hydrological processes. This research investigated the effect of drainage area ratio (i.e., the ratio of field area to VFS area) and flow concentration (i.e., uniform versus concentrated flow) on pesticide removal efficiency of a VFS and used these data to provide further field verification of a recently proposed numerical/empirical modeling procedure for predicting removal efficiency under variable flow conditions. Runoff volumes were used to simulate drainage area ratios of 15:1 and 30:1. Flow concentration was investigated based on size of the VFS by applying artificial runoff to 10% of the plot width (i.e., concentrated flow) or the full plot width (i.e., uniform flow). Artificial runoff was metered into 4.6-m long VFS plots for 90 min after a simulated rainfall of 63 mm applied over 2 h. The artificial runoff contained sediment and was dosed with chlorpyrifos and atrazine. Pesticide removal efficiency of VFS for uniform flow conditions (59% infiltration; 88% sediment removal) was 85% for chlorpyrifos and 62% for atrazine. Flow concentration reduced removal efficiencies regardless of drainage area ratio (i.e., 16% infiltration, 31% sediment removal, 21% chlorpyrifos removal, and 12% atrazine removal). Without calibration, the predictive modeling based on the integrated VFSMOD and empirical hydrologic-based pesticide trapping efficiency equation predicted atrazine and chlorpyrifos removal efficiency under uniform and concentrated flow conditions. Consideration for hydrological processes, as opposed to statistical relationships based on buffer physical characteristics, is required to adequately predict VFS pesticide trapping efficiency.

Reichenberger, S., M. Bach, A. Skitschak and H. G. Frede (2007). "Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review." <u>Sci Total Environ</u> 384(1-3): 1-35.

In this paper, the current knowledge on mitigation strategies to reduce pesticide inputs into surface water and groundwater, and their effectiveness when applied in practice is reviewed. Apart from their effectiveness in reducing pesticide inputs into ground- and surface water, the mitigation measures identified in the literature are evaluated with respect to their practicability. Those measures considered both effective and feasible are recommended for implementing at the farm and catchment scale. Finally, recommendations for modelling are provided using the identified reduction efficiencies. Roughly 180 publications directly dealing with or being somehow related to mitigation of pesticide inputs into water bodies were examined. The effectiveness of grassed buffer strips located at the lower edges of fields has been demonstrated. However, this effectiveness is very variable, and the variability cannot be explained by strip width alone. Riparian buffer strips are most probably much less effective than edge-of-field buffer strips in reducing pesticide runoff and erosion inputs into surface waters.

Constructed wetlands are promising tools for mitigating pesticide inputs via runoff/erosion and drift into surface waters, but their effectiveness still has to be demonstrated for weakly and moderately sorbing compounds. Subsurface drains are an effective mitigation measure for pesticide runoff losses from slowly permeable soils with frequent waterlogging. For the pathways drainage and leaching, the only feasible mitigation measures are application rate reduction, product substitution and shift of the application date. There are many possible effective measures of spray drift reduction. While sufficient knowledge exists for suggesting default values for the efficiency of single drift mitigation measures, little information exists on the effect of the drift reduction efficiency of combinations of measures. More research on possible interactions between different drift mitigation measures and the resulting overall drift reduction efficiency is therefore indicated. Point-source inputs can be mitigated against by increasing awareness of the farmers with regard to pesticide handling and application, and encouraging them to implement loss-reducing measures of "best management practice". In catchments dominated by diffuse inputs at least in some years, mitigation of point-source inputs alone may not be sufficient to reduce pesticide loads/concentrations in water bodies to an acceptable level.

Sabbagh, G. J., G. A. Fox, A. Kamanzi, B. Roepke and J. Z. Tang (2009). "Effectiveness of vegetative filter strips in reducing pesticide loading: quantifying pesticide trapping efficiency." J Environ Qual 38(2): 762-771.

Pesticide trapping efficiency of vegetated filter strips (VFS) is commonly predicted with low success using empirical equations based solely on physical characteristics such as width and slope. The objective of this research was to develop and evaluate an empirical model with a foundation of VFS hydrological, sedimentological, and chemical specific parameters. The literature was reviewed to pool data from five studies with hypothesized significant parameters: pesticide and soil properties, percent reduction in runoff volume (i.e., infiltration) and sedimentation, and filter strip width. The empirical model was constructed using a phase distribution parameter, defined as the ratio of pesticide mass in dissolved form to pesticide mass sorbed to sediment, along with the percent infiltration, percent sedimentation, and the percent clay content (R(2) = 0.86 and standard deviation of differences [STDD] of 7.8%). Filter strip width was not a statistically significant parameter in the empirical model. For low to moderately sorbing pesticides, the phase distribution factor became statistically insignificant; for highly sorbing pesticides, the phase distribution factor became the most statistically significant parameter. For independent model evaluation datasets, the empirical model based on infiltration and sediment reduction, the phase distribution factor, and the percent clay content (STDD of 14.5%) outperformed existing filter strip width equations (STDD of 38.7%). This research proposed a procedure linking a VFS hydrologic simulation model with the proposed empirical trapping efficiency equation. For datasets with sufficient information for the VFS modeling, the linked numerical and empirical models significantly (R(2) = 0.74) improved predictions of pesticide trapping over empirical equations based solely on physical VFS characteristics.

Sabbagh, G. J., R. Munoz-Carpena and G. A. Fox (2013). "Distinct influence of filter strips on acute and chronic pesticide aquatic environmental exposure assessments across U.S. EPA scenarios." Chemosphere 90(2): 195-202.

Vegetative filter strips (VFS) are proposed for protection of receiving water bodies and aquatic organisms from pesticides in runoff, but there is debate regarding the efficiency and filter size requirements. This debate is largely due to the belief that no quantitative methodology exists for predicting runoff buffer efficiency when conducting acute and/or chronic environmental exposure assessments. Previous research has proposed a modeling approach that links the U.S. Environmental Protection Agency's (EPA's) PRZM/EXAMS with a well-tested process-based model for VFS (VFSMOD). In this research, we apply the modeling framework to determine (1) the most important input factors for quantifying mass reductions of pesticides by VFS in aquatic exposure assessments relative to three distinct U.S. EPA scenarios encompassing a wide range of conditions; (2) the expected range in percent reductions in acute and chronic estimated environmental concentrations (EECs); and (3) the differential influence of VFS when conducting acute versus chronic exposure assessments. This research utilized three, 30-yr U.S. EPA scenarios: Illinois corn, California tomato, and Oregon wheat. A global sensitivity analysis (GSA) method identified the most important input factors based on discrete uniform probability distributions for five input factors: VFS length (VL), organic-carbon sorption coefficient (K(oc)), half-lives in both water and soil phases, and application timing. For percent reductions in acute and chronic EECs, VL and application timing were consistently the most important input factors independent of EPA scenario. The potential ranges in acute and chronic EECs varied as a function of EPA scenario and application timing. Reductions in acute EECs were typically less than percent reductions in chronic EECs because acute exposure was driven primarily by large individual rainfall and runon events. Importantly, generic specification of VFS design characteristics equal across scenarios should be avoided. The revised pesticide assessment modeling framework offers the ability to elucidate the complex and non-linear relationships that can inform targeted VFS design specifications.

Schulz, R. (2004). "Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution: a review." J Environ Qual 33(2): 419-448.

More than 60 reports of insecticide-compound detection in surface waters due to agricultural drift and run-off have been published in the open literature during the past 20 years, about one-third of them having been undertaken in the past 3.5 years. Recent reports tend to concentrate on specific routes of pesticide entry, such as runoff, but there are very few studies on spray drift-borne contamination. Reported aqueous-phase insecticide concentrations are negatively correlated with the catchment size and all concentrations of > 10 microg/L (19 out of 133) were found in smaller-scale catchments (< 100 km2). Field studies on effects of insecticide contamination often lack appropriate exposure characterization. About 15 of the 42 effect studies reviewed here revealed a clear relationship between quantified, non-experimental exposure and observed effects in situ, on abundance, drift, community structure, or dynamics. Azinphos-methyl, chlorpyrifos, and endosulfan were frequently detected at levels above those reported to reveal effects in the field; however, knowledge about effects of insecticides in the field is still sparse. Following a short overview of various risk mitigation or best management practices, constructed wetlands and vegetated ditches are described as a risk mitigation strategy that have only recently been established for agricultural insecticides. Although only 11 studies are available, the results in terms of pesticide retention and toxicity reduction are very promising. Based on the reviewed literature, recommendations are made for future research activities.

Shin, J. and K. Gil (2015). "Determination of removal efficiency using vegetative filter strips based on various efficiency evaluation methods." Environ Earth Sci 73(10): 6437-6444.

In this study, through the monitoring of 17 rainfall events over the course of a 3-year period, and in conjunction with the use of vegetative filter strips (VFS), five cases were calculated using different methods and they were evaluated in terms of the non-point source contamination removal efficiency. The efficacy of the methods used for evaluating the removal efficiencies can change considerably depending on several factors such as the removal device type, drainage basin, and rainfall event. With VFS, the removal efficiencies were found to change in accordance with the vegetation coverage ratio, except in June and July, which for watersheds in Korea are the months when rainfall amounts are concentrated. As such, it is assumed that because the VFS removal efficiencies are significantly affected by the vegetation coverage ratio, a method that explicitly considers the vegetation coverage ratio would be most appropriate when calculating the efficiency of a removal facility such as VFS.

Tang, X., B. Zhu and H. Katou (2012). "A review of rapid transport of pesticides from sloping farmland to surface waters: processes and mitigation strategies." J Environ Sci (China) 24(3): 351-361.

Pesticides applied to sloping farmland may lead to surface water contamination through rapid transport processes as influenced by the complex topography and high spatial variability of soil properties and land use in hilly or mountainous regions. However, the fate of pesticides applied to sloping farmland has not been sufficiently elucidated. This article reviews the current understanding of pesticide transport from sloping farmland to surface water. It examines overland flow and subsurface lateral flow in areas where surface soil is underlain by impervious subsoil or rocks and tile drains. It stresses the importance of quantifying and modeling the contributions of various pathways to rapid pesticide loss at catchment and regional scales. Such models could be used in scenario studies for evaluating the effectiveness of possible mitigation strategies such as constructing vegetated strips, depressions, wetlands and drainage ditches, and implementing good agricultural practices. Field monitoring studies should also be conducted to calibrate and validate the transport models as well as biophysical-economic models, to optimize mitigation measures in areas dominated by sloping farmland.

Winchell, M. F., R. L. Jones and T. L. Estes (2011). Comparison of models for estimating the removal of pesticides by vegetated filter strips. Pesticide Mitigation Strategies for Surface Water Quality, American Chemical Society. 1075: 273-286.

Vegetated filter strips (VFSs) established at the downslope edge of agricultural fields have long been recommended as a management practice to reduce sediment, nutrients, and pesticides in surface runoff before it enters water bodies. Recently VFSs have been mandated as label requirements for plant protection products in Europe and North America. Several simulation models have been developed to predict the amount of pesticide active ingredients and their metabolites removed from runoff flowing through these strips. Removal efficiency is a function of several parameters and must be predicted on an event basis. The predictions of four simulation models (APEX, PRZM-BUFF, REMM, and VFSMOD) were compared using three data sets. Conditions simulated included a range of soil properties, slopes, rainfall events, and pesticide characteristics. All four models predicted reductions of pesticides in the VSFs consistent with the observed reductions, with VFSMOD simulations in closest agreement with the measured data across the three data sets.

Yang, F., Y. Yang, H. Li and M. Cao (2015). "Removal efficiencies of vegetation-specific filter strips on nonpoint source pollutants." Ecol Eng 82: 145-158.

A field experiment was conducted to examine the removal efficiencies of different autochthonous vegetation-specific filter strips on nonpoint source pollutants (NPSPs) and to identify their major influencing factors under various conditions. Furthermore, the effects of five major influencing factors on the removal efficiencies were analyzed. We found that the removal efficiencies in total suspended solid (SS), total nitrogen (TN) and total phosphorus (TP) of the grass vegetation filter strip were significantly higher than those of the seabuckthorn bushy vegetation filter strip. The averaged SS concentration and mass removal efficiencies of the VFS were commonly above 90%, respectively. The TN concentration removal efficiency ranged from 50 to 70%, and the mean TN mass removal efficiency ranged from 70 to 90%. The mean concentration and mass removal efficiencies in particulate nitrogen (PN) were approximately 85 and 95%, respectively. However, the concentration and mass efficiencies in dissolved nitrogen (DN) were lower. The TP concentration removal efficiency averaged 86%, and the mean TP mass removal efficiency was about 94%. The mean concentration and mass removal efficiencies in particulate phosphorus (PP) were approximately 88 and 96%, respectively. Moreover, the concentration and mass efficiencies in dissolved phosphorus (DP) were not significantly high. This suggests that PN is the main loss form of N and PP is the major loss form of P. Overall, the mass removal efficiencies of various species of VFS on nonpoint source pollutants in various forms were higher than the concentration removal efficiencies. Additionally, the removal efficiencies of VFS on nonpoint source pollutants were subject to many factors such as vegetation coverage, initial soil water content, width of VFS, inflow discharge and inflow concentration. However, the most important influencing factors are vegetation coverage, width of VFS and inflow concentration. The width of VFS plays an essential role in N and P removal efficiencies, in that even though the width of VFS is longer, the removal efficiency of VFS is not really better. Additionally, the removal of SS should be firstly considered during the course of the application of VFS due to the SS correlating well linearly with TN and TP. Nevertheless, routine maintenance is also quite necessary to keep in good removal performance of VFS.

REVIEW OF PESTICIDE RETENTION PROCESSES OCCURRING IN BUFFER STRIPS RECEIVING AGRICULTURAL RUNOFF

Kapil Arora, Steven K. Mickelson, Matthew J. Helmers, and James L. Baker. Review of Pesticide Retention Processes Occurring in Buffer Strips Receiving Agricultural Runoff. <u>Journal of the American Water Resources Association</u> 46(3):618-647.

Review of the published results shows that the retention of the two pesticide carrier phases (runoff volume and sediment mass) influences pesticide mass transport through buffer strips. Data averaged across different studies showed that the buffer strips retained 45% of runoff volume (ranging between 0 and 100%) and 76% of sediment mass (ranging between 2 and 100%). Sorption (soil sorption coefficient, Koc) is one key pesticide property affecting its transport with the two carrier phases through buffer strips. Data from different studies for pesticide mass retention for weakly (Koc < 100), moderately (100 < Koc < 1,000), and strongly sorbed pesticides (Koc > 1,000) averaged (with ranges) 61 (0-100), 63 (0-100), and 76 (53-100) %, respectively. Because there are more data for runoff volume and sediment mass retention, the average retentions of both carrier phases were used to calculate that the buffer strips would retain 45% of weakly to moderately sorbed and 70% of strongly sorbed pesticides on an average basis. As pesticide mass retention presented is only an average across several studies with different experimental setups, the application of these results to actual field conditions should be carefully examined.

Krutz, L. J., S. A. Senseman, R. M. Zablotowicz and M. A. Matocha (2005). "Reducing herbicide runoff from agricultural fields with vegetative filter strips: A review." <u>Weed Sci</u> 53(3): 353-367.

A review. Although the effectiveness of vegetative filter strips (VFS) for reducing herbicide runoff is well documented, a comprehensive review of the literature does not exist. The objectives of this article are to denote the methods developed for evaluating herbicide retention in VFS; ascertain the efficacy of VFS regarding abating herbicide runoff; identify parameters that affect herbicide retention in VFS; review the environmental fate of herbicides retained by VFS; and identify future research needs. The retention of herbicide runoff by VFS has been evaluated in natural rainfall, simulated rainfall, and simulated run-on experiments. Parameters affecting herbicide retention in VFS include width of VFS, area ratio, species established in the VFS, time after establishment of the VFS, antecedent moisture content, nominal herbicide inflow concentration, and herbicide properties. Generally, subsequent transport of herbicides retained by VFS is reduced relative to adjacent cultivated soil because of enhanced sorption and degradation in the former.

Otto, S., A. Cardinali, E. Marotta, C. Paradisi and G. Zanin (2012). "Effect of vegetative filter strips on herbicide runoff under various types of rainfall." Chemosphere 88(1): 113-119.

Narrow vegetative filter strips proved to effectively reduce herbicide runoff from cultivated fields mainly due to the ability of vegetation to delay surface runoff, promote infiltration and adsorb herbicides. A field trial was conducted from 2007 to 2009 in north-east Italy in order to evaluate the effectiveness of various types of vegetative filter strips to reduce spring-summer runoff of the herbicides mesotrione, metolachlor and terbuthylazine, widely used in maize, and to evaluate the effect of the rainfall characteristics on the runoff volume and concentration. Results show that without vegetative filter strip the herbicide load that reaches the surface water is about 5-6 g ha(-1)year(-1) for metolachlor and terbuthylazine (i.e. 0.5-0.9% of the applied rate), confirming that runoff from flat fields as in the Po Valley can have a minor effect on the water quality, and that most of the risk is posed by a few, or even just one extreme rainfall event with a return period of about 25-27 years, causing runoff with a maximum concentration of 64-77 ug L(-1). Mesotrione instead showed rapid soil disappearance and was observed at a concentration of 1.0-3.8mug L(-1) only after one extreme (artificial) rainfall. Vegetative filter strips of any type are generally effective and can reduce herbicide runoff by 80-88%. Their effectiveness is steady even under severe rainfall conditions, and this supports their implementation in an environmental regulatory scheme at a catchment or regional scale.

Otto, S., M. Vianello, A. Infantino, G. Zanin and A. Di Guardo (2008). "Effect of a full-grown vegetative filter strip on herbicide runoff: maintaining of filter capacity over time." Chemosphere 71(1): 74-82.

Narrow vegetative filter strips (VFS) proved to effectively reduce herbicide runoff from cultivated fields mainly due to the ability of vegetation to delay surface runoff, promote infiltration and adsorb herbicides. Since VFS are dynamic systems, their performance would not remain constant over the years indicating the need to define suitable buffer management. In order to evaluate the performance of different five and six year-old VFS, the runoff of the herbicides metolachlor and terbuthylazine was monitored in 2002 and 2003 in an experimental site in northern Italy. The structure of the herbaceous cover in the buffers changes over time. When rows of trees are present, the grass cover is decreased by the shading action of the trees, but the leaf litter gains importance. In VFS with grass cover only, the cover composition changes because of the substitution of grass by broadleaf species. Six meter wide VFS are very effective in reducing runoff volume and concentration during both wet and dry years. Classification analysis showed that runoff concentration and volume are linked to the characteristics of the rainfall event, buffer, source of herbicides and time after application. Regression analysis showed that the significant predictors for runoff volume are rainfall amount and intensity, total vegetal cover in the VFS, crop leaf area index and time after treatment; for concentration they are rainfall intensity, crop leaf area index and total vegetal cover in the VFS. The role of VFS is complex, so appropriate management is required to maintain its increasing filtering capacity over time.

Sabbagh, G. J., G. A. Fox, R. Munoz-Carpena and M. F. Lenz (2010). "Revised framework for pesticide aquatic environmental exposure assessment that accounts for vegetative filter strips." Environ Sci Technol 44(10): 3839-3845.

For pesticides that do not pass higher-level environmental exposure assessments, vegetated filter strips (VFS) are often mandated for use of the compound. However, VFS physiographic characteristics (i.e., width) are not currently specified based on predictive modeling of VFS performance. This has been due to the lack of predictive tools that can explain the wide range of field-reported efficacies. This research hypothesizes that mechanistic modeling of VFS runoff and sediment trapping, integrated with an empirical, regression-based pesticide trapping equation and the U.S. Environmental Protection Agency's (EPA) exposure framework, is able to effectively derive these VFS characteristics. To test this hypothesis, a well-tested process-based model for VFS (VFSMOD) was coupled with the pesticide trapping equation and integrated with EPA's PRZM/EXAMS exposure package. The revised framework was applied to a prescribed U.S. EPA assessment scenario for four hypothetical pesticides: more mobile (i.e., organic carbon (OC) sorption coefficients, K(oc), of 100 L/kg OC) and less mobile (2000 L/kg OC) pesticides that are fast degrading or stable (i.e., 10 or 10,000 d aquatic dissipation half-lives). A nonlinear and complex relationship was observed between pesticide reduction, VFS length, and rainfall plus run-on event size. The impact of VFS on environmental exposure concentrations (EECs) was found to be dependent on the pesticide sorption and dissipation half-life and whether calculating an acute or chronic EEC. While acute and chronic EECs were equivalent for stable pesticides, for fast degrading pesticides the acute EEC depended on specific loading events. Therefore, while VFS may reduce the cumulative pesticide loading, a corresponding reduction in the acute EEC may not always be observed. Such results emphasize the need to incorporate physically based modeling of VFS reductions for pesticides that do not pass the current U.S. EPA exposure assessment framework.

Patzold, S., C. Klein and G. W. Brummer (2007). "Run-off transport of herbicides during natural and simulated rainfall and its reduction by vegetated filter strips." Soil Use Manag 23(3): 294-305.

The efficiency of filter strips in protecting watercourses against herbicides in run-off was evaluated in field experiments in western Germany. Surface run-off caused by natural rainfall and related transport of metolachlor, terbuthylazine and pendimethalin were measured on plots of 40 m length without filter strips (F0), and after passing over three types of herbicide-untreated field margin: 12 m conservation headland (CH12), 6 m (GF6) and 12 m grass strips (GF12). Run-off was also measured after simulated rainfall on 7 m long plots without (F0) and with 3 m grass strips (GF3). All three herbicides were transported both in dissolved and in adsorbed forms; the partitioning depended on their water solubility with metolachlor and terbuthylazine mainly translocated in dissolved form (F0: highest mean concentrations for a natural run-off event 721 and 220 micro g L⁻¹, respectively). Pendimethalin was predominantly transported in adsorbed form (maximum mean concentration 11.2 ug L(-1). In the sediment, the highest mean herbicide contents in a single natural event (F0) accounted for 2294 ug kg(-1) (metolachlor), 1317 ug kg(-1) (terbuthylazine) and 5648 ug kg(-1)(pendimethalin). The proportions of applied herbicide translocated were 0.3% (metolachlor), 0.2% (terbuthylazine) and 0.06% (pendimethalin; F0, natural rainfall). The extent of herbicide transport decreased with time but within this trend soil sealing, soil moisture and amount and intensity of rainfall increased losses. Compared with the F0 plots, the reduction of herbicide translocation after natural rainfall reached 80-83% (CH12), 80-88% (GF6) and >99% (GF12) over the 3-year period. The 12 m grass strips allowed only one extreme run-off event to pass through, thus providing a highly effective zone because of the large decrease (68%) in flow. The average buffer reduced loadings for all nutrient species, from 27% for TKN to 63% for sediment P. The managed forest and grass buffer combined offered effective watercourse protection against herbicide pollution.

Stehle, S., D. Elsaesser, C. Gregoire, G. Imfeld, E. Niehaus, E. Passeport, S. Payraudeau, R. B. Schafer, J. Tournebize and R. Schulz (2011). "Pesticide risk mitigation by vegetated treatment systems: a meta-analysis." J Environ Qual 40(4): 1068-1080.

Pesticides entering agricultural surface waters threaten water quality and aquatic communities. Recently, vegetated treatment systems (VTSs) (e.g., constructed wetlands and vegetated ditches) have been proposed as pesticide risk mitigation measures. However, little is known about the effectiveness of VTSs in controlling nonpoint source pesticide pollution and factors relevant for pesticide retention within these systems. Here, we conducted a meta-analysis on pesticide mitigation by VTSs using data from the scientific literature and the European LIFE ArtWET project. Overall, VTSs effectively reduced pesticide exposure levels (i.e., the majority of pesticide retention performances was >70%). A multiple linear regression analysis of 188 retention performance cases identified the two pesticide properties, organic carbon sorption coefficient value and water-phase 50% dissipation time, as well as the VTS characteristics overall plant coverage and hydraulic retention time for targeting high efficacy of pesticide retention. The application of a Tier I risk assessment (EU Uniform Principle) revealed a higher toxicity reduction for hydrophobic and nonpersistent insecticides compared with less sorptive and not readily degradable herbicides and fungicides. Overall, nearly half (48.5%) of all pesticide field concentrations (n = 130) failed Tier I standard risk assessment at the inlet of VTSs, and 29.2% of all outlet concentrations exceeded conservative acute threshold levels. We conclude that VTSs are a suitable and effective risk mitigation strategy for agricultural nonpoint source pesticide pollution of surface waters. Further research is needed to improve their overall efficacy in retaining pesticides.

Zhang, X., X. Liu, M. Zhang, R. A. Dahlgren and M. Eitzel (2010). "A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution." J Environ Qual 39(1): 76-84.

Vegetated buffers are a well-studied and widely used agricultural management practice for reducing nonpoint-source pollution. A wealth of literature provides experimental data on their mitigation efficacy. This paper aggregated many of these results and performed a meta-analysis to quantify the relationships between pollutant removal efficacy and buffer width, buffer slope, soil type, and vegetation type. Theoretical models for removal efficacy (Y) vs. buffer width (w) were derived and tested against data from the surveyed literature using statistical analyses. A model of the form Y = K x (1-e(-bxw)), (0 < K < or = 100) successfully captured the relationship between buffer width and pollutant removal, where K reflects the maximum removal efficacy of the buffer and b reflects its probability to remove any single particle of pollutant in a unit distance. Buffer width alone explains 37, 60, 44, and 35% of the total variance in removal efficacy for sediment, pesticides, N, and P, respectively. Buffer slope was linearly associated with sediment removal efficacy either positively (when slope < or = 10%) or negatively (when slope > 10%). Buffers composed of trees have higher N and P removal efficacy than buffers composed of grasses or mixtures of grasses and trees. Soil drainage type did not show a significant effect on pollutant removal efficacy. Based on our analysis, a 30 m buffer under favorable slope conditions (approximately 10%) removes more than 85% of all the studied pollutants. These models predicting optimal buffer width/slope can be instrumental in the design, implementation, and modeling of vegetated buffers for treating agricultural runoff.

Cardinali, A., S. Otto and G. Zanin (2013). "Herbicides runoff in vegetative filter strips: evaluation and validation of a recent rainfall return period model." Int J Environ Anal Chem 93(15): 1628-1637.

Vegetative filter strips reduce herbicide runoff from cultivated fields owing to the ability of vegetation to delay surface runoff, promote infiltration, and adsorb herbicides. Previous research has shown that the annual runoff of each herbicide is typically less than 1 g ha-1. A model for the detection of the return period of rainfall events was recently proposed for a site in the north-eastern Po Valley, Italy. The return period model suggested that most of the herbicide loss by runoff (about 98%) is caused by a few, or even just one, extreme rainfall event with a return period of about 25-27 years, whereas ordinary events (4-5 each year) account for the rest. The present study aims to validate that model by comparing model predictions with the exptl. results obtained in the 2010-2011 sampling season (independent test data), and to evaluate the effectiveness of the VFS. In addn., a 7-yr dataset of metolachlor and terbuthylazine concentration in real runoff events is summarized in order to highlight the medium-term magnitude of the pollution. Results show that on the Po Valley plain, 3-4 runoff events of low intensity are expected in spring-summer and that the consequent annual runoff of the herbicides metolachlor and terbuthylazine is about 0.5-0.7 g ha-1 yr-1. A summary shows that, owing to their chem.-phys. properties, concentrations of the two herbicides are similar, both varying from about 0.01-300 µg L-1, with a potential pulse-like exposure risk for aquatic communities in waterways. This study showed that vegetative filter strips can reduce herbicide transfer to surface water by 90-98%, and should be suggested for environmental schemes at field and catchment scale.