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Agroforestry for sustainable agriculture

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Contents

Part 3 Agroforestry products

Introduction

The United States Department of Agriculture (USDA) defines agroforestry as: 'the intentional mixing of trees and shrubs into crop and animal production systems to create environmental, economic and social benefits'. Agroforestry seeks to balance the protection of forest resources, the exploitation of the ecosystem services that trees can contribute to agriculture and the role of agroforestry in diversifying the range of agricultural products and markets. The book provides a comprehensive review of ways of optimizing particular agroforestry practices, from riparian forest buffers and windbreaks to alley cropping, silvopasture and forest farming. In addition, the volume summarises current research on ecosystem services delivered by agroforestry in such areas as habitat conservation and soil health. The book also assesses research on optimising agroforestry products such as timber, nuts and fruit. The main focus of the book is on temperate agroforestry, but it also reviews particular issues facing agroforestry in the tropics.

Part 1 Agroforestry practices

The first part of the volume addresses agroforestry practices. The subject of Chapter 1 is riparian forest buffers and filter strips. Riparian forest buffers are planned combinations of trees, shrubs, grasses, forbs and bioengineered structures adjacent to or within a stream channel designed to mitigate the impact of land use on the stream or creek. At the landscape level, riparian forest buffers link the land and aquatic environment and perform vital ecological functions as part of the network of watersheds that connect forest, prairies, agricultural and urban lands. Following an introduction to the concept of riparian forest buffers, the chapter examines forest buffer design and function. The chapter discusses the distinct management zones in a riparian forest buffer, including undisturbed forest, managed forest and shrubs, and runoff control (grasses and forbs). The chapter concludes with sections on special design considerations and management, as well as ways of assessing buffer performance.

Chapter 2 moves on from riparian buffers to consider the role of windbreaks. Windbreaks, also known as vegetative environmental buffers (VEB) or shelterbelts, are a common feature of agricultural systems around the world. These strips of trees, shrubs and other perennial or annual vegetation perform a number of functions, including providing protection from the wind for homesteads, livestock and crops; reducing soil erosion; providing protection from drifting snow; providing wildlife habitat; and enhancing aesthetics in agricultural landscapes. The chapter offers an overview of the benefits of windbreaks and examines the process of tree and shrub selection and planting.

The chapter looks at designing windbreaks to reduce wind speed and snow drift, as well as describing the use of windbreaks for particulate capture, odor mitigation and wildlife conservation.

Chapter 3 shifts the focus to managing hedgerows in order to optimise ecosystem services in agroforestry systems. Hedgerows are composed of trees and/or shrubs and serve as natural fences, often between pastures and arable fields. The chapter discusses the importance of hedgerow management and maintenance to enhance multiple ecosystem services such as biomass production, wind and water protection, habitat provision and landscape aesthetics. It develops a categorisation of existing hedgerows, applicable to linear woody-features such as hedgerows, windbreaks and riparian buffer strips, and evaluates the condition of each category with respect to multiple ecosystem services. The chapter considers different measures for improving hedgerow conditions and provides guidelines for hedgerow restoration and management. The chapter includes a case study on hedgerow management, focusing on estimating the biomass potential of hedgerows and the implementation of a restoration and management strategy to selected hedgerows in two different scenarios.

The subject of Chapter 4 is temperate alley cropping systems. The implementation of modern agricultural practices has largely excluded trees from the rural landscape, causing negative environmental impacts. Alley cropping, an agroforestry practice where agricultural crops are grown simultaneously with long-term tree crops, helps mitigate negative environmental impacts and offers a promising land-use alternative to conventional farming for temperate regions. The chapter provides an overview of economic and ecological benefits, challenges, and major considerations of implementing these practices within North America. To illustrate the key issues, the chapter focuses on a system performance evaluation of a pecan-cotton system in the southern United States.

Chapter 5 moves on to consider silvopastoralism, a traditional agroforestry practice that is still used across the world for raising livestock, particularly in lands with a combination of grass understory and a sparse cover of trees and/or shrubs. The woody component plays multiple roles such as providing a forage resource, shade and shelter for livestock and delivering products such as timber, firewood or cork, for example. The chapter describes silvopastoral systems from around the world. The chapter also includes a section on the role of trees in promoting ecosystems services such as carbon sequestration, water quality and biodiversity conservation. The chapter concludes with a discussion of how to design and manage silvopastures.

Staying with the theme of diverse agroforestry, Chapter 6 examines forest farming. This is a relatively low-tech agroforestry practice for the cultivation of shade-tolerant non-timber forest products (NTFPs) such as medicinal plants, mushrooms, fruits, nuts, tree syrups and/or nursery stock. It is an ecologically sustainable way for forest owners to generate income, while maintaining forest health (also known as productive conservation). The chapter introduces the concept of forest farming with sections on both estimating yields and how to select sites for such practices. The chapter discusses the products with the greatest potential for income generation, such as shiitake mushrooms (*Lentinula edodes*), where logs begin yielding relatively soon after their inoculation, and American ginseng (*Panax quinquefolium*) which has greater income generating potential even though it requires many years before it begins to yield. Other NTFPs are also covered including medicinal plants, fruits, nuts and tree syrups. The chapter concludes with two case studies, one on the forest farming of tree nuts, and the other on the production of wild leeks (*Allium tricocchum*).

Moving from specific practices to an overview, Chapter 7 looks at the modelling of agroforestry systems, which can be highly complex in nature. The chapter examines the current state of agroforestry modelling before going on to describe two European agroforestry projects that involved modelling, the Silvoarable Agroforestry For Europe (SAFE) project and the AGroFORestry that Will Advance Rural Development (AGFORWARD) project. Looking towards the future, the chapter also considers current agroforestry modelling needs and potential trends.

The final chapter in the section, Chapter 8, deals with tree planting and management in agroforestry. The pattern of tree planting and tree management play an important part in the sustainability of an agroforestry system, as they determine the intensity of competition between trees and crop and the quality and quantity of wood production. The chapter focuses on the plantation and management of temperate agroforestry systems combining timber trees and herbaceous crops. The chapter covers choice of tree species, techniques of tree planting, plantation maintenance and approaches to tree pruning and thinning.

Part 2 Agroforestry ecosystem services

Opening the second part of the volume, which focuses on agroforestry ecosystem services, Chapter 9 turns to the relationship between trees, science and global society. Despite great advances in our understanding of the environmental, social and economic role of trees in farming systems, much work still remains to be done, especially regarding the wider adoption of agroforestry practices. The chapter offers an overview of tree agroecology, tree domestication, the commercialization of trees and the relevance of development studies to this field. The chapter assesses the potential for up-scaling the exploitation of trees as a sustainable resource and examines relevant issues connected with government policy and agribusiness.

Following this overview, Chapter 10 homes in on the role of agroforestry in habitat conservation and biodiversity. Agricultural biodiversity, commonly referred to as agrobiodiversity, focuses on agricultural habitats and food production landscapes. Adopting a multi-dimensional approach to their management is essential to ensure the sustainability of agricultural habitats. The chapter describes the application of the food system concept in providing a framework to enable such a multi-dimensional approach. The chapter outlines the multiple dimensions of food security and places food security in the context of global environment change. Finally, the chapter explains the concept of multifactor food security promotion.

The focus of Chapter 11 is on agroforestry as a system for improving soil health. Introducing agroforestry into agroecosystems can be an important method to help promote soil quality through its influence on soil physical, chemical and biological properties. The chapter highlights the benefits of agroforestry systems on soil properties important for soil quality. These include critical soil biological, physical and chemical properties important for maintaining and improving soil health. The chapter outlines the critical soil biological properties important for energy and nutrient transformations, as well as critical soil physical properties including soil density, porosity, water retention, pore-size distributions, hydraulic conductivity, infiltration, and thermal properties. The chapter shows that improving these parameters can reduce losses of sediment, nutrients and pesticides from land to water, and enhance soil water storage.

Part 3 Agroforestry products

The third part of the volume is dedicated to the diverse products of agroforestry. Chapter 12 examines the contribution of agroforestry to hardwood timber production. Managing hardwood trees for high-quality sawlogs within the agroforestry practices of alley-cropping, silvopasture, forested riparian buffers and upland (windbreaks) buffers means intensively managing relatively wide-spaced trees and a ground cover as a companion crop on the same unit of land. The chapter synthesizes available information on managing such trees for the production of veneer and high-quality sawlogs. The chapter includes sections on the impact of ground cover on tree growth and growing space requirements for hardwoods. The chapter also looks at pruning recommendations and practices, since pruning is essential for the production of high-quality logs of most species in any agroforestry practice. The chapter concludes with a section on log and wood quality and the general requirements of veneer logs.

The section then moves on to an assessment of the cultivation of nuts in Chapter 13. Row crop agriculture covers over 1.28 billion hectares of land globally. Though extremely productive in terms of yield, annual cropping systems rely on external inputs of energy, nutrients, and pesticides, leading to a suite of ecological consequences. The chapter focusses primarily on the opportunities and challenges associated with alley cropping practices involving overstory nut crops as one element of the solution to address global needs for food production which is both economically viable while enhancing ecosystem services. The chapter examines key challenges facing nut-based agroforestry systems, looking at the genetic improvement of nut trees as well as the challenge of managing temporal and spatial tree and crop interactions. The chapter addresses orchard design and management, pest management in nut tree alley cropping, and financial decision support tools.

The final chapter in Part 3 is Chapter 14 which reviews agroforestry for fruit trees. Although fruit trees are considered as high value for agroforestry and are the primary driver of agroforestry adoption worldwide, they are still underrepresented in agroforestry systems in temperate regions compared to the tropics. This chapter illustrates the large diversity of fruit tree-based agroforestry in Europe and in the Mediterranean North Africa. The chapter then describes the most common species-based (apple, olive) and place-based (e.g. oasis) agroforestry systems in these regions. Finally, the chapter discusses key biological and agronomical requirements of fruit trees that have to be considered when implementing successful fruit-tree based agroforestry systems. It reviews current trends in the design of agronomically and ecologically-sound fruit tree-based agroforestry systems.

Part 4 Tropical agroforestry

The volume's final section deals with agroforestry in tropical areas. Chapter 15 addresses the challenges involved in tropical agroforestry. From its early beginnings, agroforestry has moved from a 'technology in search of a problem' to a principal solution to critical global agendas, including climate smart agriculture, agroecological intensification, land rehabilitation, and provision of ecosystem services. The chapter addresses the challenges associated with agroforestry in agroecological intensification and sustainable landscapes. The chapter considers the challenge of developing policies in support of agroforestry, and the challenge of developing agroforestry at scale.

The subject of Chapter 16 is tropical tree domestication in agroforestry. The chapter examines the principles and techniques of tropical tree domestication, covering identification of species for domestication, selection of 'plus trees' and vegetative propagation methods. The chapter then provides examples of key tree species that have been targeted for domestication in the Amazon Basin (*Bactris gasipaes*, *Capirona*, *Guazuma crinita* and *Inga edulis*) and the Congo Basin (*Irvingia gabonensis*, *Irvingia wombolu*, safou, *Ricinodendron heudelotii*, *Cola acuminata*, *Cola anomala*, *Cola nitida* and *Prunus africana*). The chapter concludes with a case study on participatory domestication of *Allanblackia floribunda*, a high value agroforestry tree species in Central Africa.

The volume's final chapter, Chapter 17, looks at trade-off analysis for better design strategies in tropical agroforestry and ecosystem services. A large body of research has documented a wide list of provisioning and regulating services that can be provided by tropical agroforestry systems (AFS). The chapter offers an overview of ecosystem services delivered by tropical AFS, and presents practical approaches for trade-off analysis between ecosystem services and plant biodiversity for better design (or re-design) and management of AFS. The chapter highlights the main provisioning and regulating services provided by tropical AFS (covering pest and disease regulation, nutrient cycling and soil quality, carbon sequestration and water regulation). The chapter gives an overview of practical approaches to assess trade-offs provides a case study of trade-off analysis in practice.

Part 1

Agroforestry practices

Chapter 1

Agroforestry practices: riparian forest buffers and filter strips

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1 Introduction

Intensive agriculture as practiced in much of the Temperate Zone around the world is not very friendly to the environment. Non-point source (NPS) pollution from this kind of agriculture has created major water quality issues for surface waters that originate or flow through these areas (Veum et al., 2009). In many landscapes in the Midwestern United States, more than 85% of the land is devoted to row crop agriculture or intensive grazing (Burkart et al., 1994). Small farms continue to be consolidated into larger farms in response to the need for economies of scale. In states east of the Rocky Mountains, vast areas are used to produce wheat, maize, soybeans and sorghum and to graze cattle (NRCS–USDA). Farm equipment that is operated by one person continues to become more sophisticated and able to cultivate and harvest larger and larger fields. The cost of the equipment and of labour further supports the continued expansion of large crop fields which are dependent on significant use of fertilizers and pesticides to optimize yields. In addition, to diversify income streams, farmers may fence off areas such as those along tightly meandering streams that are not suited to intensive crop production and graze livestock that usually have access to the streams within the fenced pastures. Livestock access to streams can do major damage to streambanks and stream water quality.

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These trends of more intensive use of all available land in agricultural regions are likely to continue with the growing world population. Increased surface run-off laden with sediment and agrochemicals and streambank collapse continue to provide higher and more frequent peak stream flows. These are characterized by high sediment and agrochemical loads that result in more flooding, incision and widening of stream channels, reduction of base flows and reduction in water quality and the quality of aquatic ecosystems.

Despite our best efforts, it is unlikely that significant reduction in nutrient and sediment loading to surface waters will be achieved through voluntary, traditional in-field management alone (Dinnes et al., 2002). Increased use, by some farmers, of techniques such as cover crops, frequent side-dressing of small amounts of fertilizer, slow release fertilizer to promote soil and water quality, nutrient cycling efficiency and crop productivity have been studied as a way to reduce nutrient and sediment loading to surface waters and some farmers are using them (Snapp et al., 2005). However, they have some disadvantages, including increased farming costs, delay of spring soil warming and making it more difficult to predict nitrogen (N) mineralization, creating challenges to widespread adoption of such practices (Roesch-McNally et al., 2017).

The Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) National Water Quality Initiative is designed to provide both in-field and edge-of-field practices such as buffer and filter strips to promote soil health, reduce erosion and lessen nutrient run-off (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/water/?cid=stelprdb1047761). One of the major NRCS Conservation Practice Standards is the Riparian Forest Buffer Standard (Practice 391). In those watersheds where the programme has been available, over 3600 farmers have taken advantage of the programme (Brewer, 2002). However, in the first 8 years of the programme, only 825 000 acres of farmland in the priority watersheds were enrolled with 11 impaired water bodies improved to the point of being removed from the US Environmental Protection Agency Impaired Waters List (USEPA 303(d) list). There are more than 390 million acres of cropland in the United States, many of them in need of conservation practices that protect surface waters (USDA 2012 Census of Agriculture).

2 Riparian forest buffers

Riparian forest buffers are an agroforestry practice that, when properly applied to the agricultural landscape, can enhance and diversify farm income opportunities, improve the environment and create wildlife habitat (Schultz et al., 2009). By developing an understanding of the interactions between the trees, shrubs and native prairie plants or introduced grasses, buffers can be designed to capture most surface run-off before it reaches the stream channel while also stabilizing the banks of the stream channel.

Riparian forest buffers are planned combinations of trees, shrubs, grasses, forbs and bioengineered structures adjacent to or within a stream channel designed to mitigate the impact of land use on the stream or creek. At the landscape level, riparian forest buffers link the land and aquatic environment and perform vital ecological functions as part of the network of watersheds that connect forests, prairies, agricultural and urban lands. By establishing and managing the trees, shrubs, grasses and forbs in the riparian zone, water quality and the aquatic ecosystems can be maintained or enhanced and the impact of floods can be mitigated. However, to be effective, riparian buffers must include plants that are adapted to the soils, topography and flood regime of the riparian zone and the stream as well as the long-term management by the landowner.

A well-established and maintained riparian forest buffer can:

- protect and improve water quality;
- stabilize eroding streambanks;
- help reduce flood impacts;
- recharge shallow groundwater;
- supply diverse food and cover for upland wildlife;
- enhance biodiversity of the landscape;
- improve carbon sequestration;
- improve aquatic habitats for fish and other organisms; and
- generate farm income from products harvested from the buffer.

An overview of the environmental benefits of riparian and other types of buffers has been provided by Lovell and Sullivan (2006) and Gundersen et al. (2010). The role of riparian and other agroforestry techniques in preventing nutrient run-off and NPS pollution is reviewed in Udawatta et al. (2002, 2006, 2011), Lee et al. (2003) and Simpkins et al. (2003). The impact of riparian buffers in enhancing water quality, preventing sediment trapping and streambank erosion is discussed in Zaimes et al. (2004), Liu et al. (2008), Klapproth and Johnson (2009a) and Udawatta et al. (2010). The broader potential contribution of riparian buffers and forests to carbon sequestration is reviewed in Dybala et al. (2019), while the biodiversity and broader social benefits they provide are discussed in Klapproth and Johnson (2009b,c).

Before designing and establishing a riparian buffer, it is critical to understand upland plant communities and their present management, the objectives of the landowner interested in installing a riparian forest buffer and their willingness and ability to manage that buffer.

Landowner concerns associated with establishment of buffers can include concerns such as:

- how much can buffers reduce sediment and nutrient movement into a stream;
- can buffers be used to heal gullies;
- can buffers reduce streambank erosion and slow stream meandering;
- what kind of buffer vegetation produces the best wildlife habitat and fishery;
- will trees in a riparian forest buffer fall into the stream and back up water into crop fields and field drainage tiles;
- are buffers a source of weed seeds;
- are cool-season grass filters as effective as riparian forest buffers;
- will forest buffers attract beavers that build dams that back up water;
- will deer become a problem for crops;
- how much maintenance is required to keep a buffer functioning properly;
- will a buffer be damaged by floods;
- is fencing needed to keep livestock out of a buffer;
- how much land will be taken out of crop production or pasture; and
- can specific products be harvested from the buffer to offset income losses from the land and similar other questions.

Riparian buffers can take different forms in response to landowner objectives and concerns as well as the regional location of the streams being buffered. Riparian forest buffers in agricultural landscapes in the Eastern United States, for example, may contain narrow corridors of remnant forests along streams with little else being needed to create an effective buffer of crop field run-off other than a grass filter lying between the crop field and the existing forest buffer. In the arid and semi-arid west, riparian forest buffers may consist of narrow strips of native flood plain species that often lie between grazed shrub and short grass communities and the stream. In the agricultural belt of the Midwestern United States, riparian forest buffers often need to be established from scratch.

Because riparian forest communities naturally evolved in the most fertile and moist position of the landscape, they are often easy to reestablish. However, in many agricultural landscapes, land uses have changed the hydrology so dramatically that the hydrology of these communities cannot be restored to their original condition. Stream channels have been incised and widened by higher discharge resulting from greater surface run-off from crop fields and heavily grazed pastures. Channelization of meandering streams, field tiling of some landscapes and urbanization also have contributed to higher stormflows and lower base flows. In many cases, water tables have been lowered to the point that the restored buffers require a plant community that did not naturally occur in that location. However, with proper planning and design the function of a healthy riparian forest community can be reestablished.

3 Riparian forest buffer design and function

Riparian forest buffers typically should be composed of three distinct management zones (Fig. 1):

- Zone 1: Undisturbed forest
- Zone 2: Managed forest and shrubs
- Zone 3: Run-off control (grasses and forbs)

These zones contain different kinds of plantings with different functions.

Zone 1 includes a zone of trees whose major function is to stabilize the streambank, provide a large long-term nutrient sink, help improve soil quality through annual leaf litterfall, provide vertical structure for wildlife habitat and potentially provide some shade to the stream channel to help stabilize daily stream water temperature especially if the desired fishery includes cold water demanding species such as trout (Table 1).

Trees should not be placed so close to the edge of the bank that they completely shade the stream throughout the whole day once they are mature.

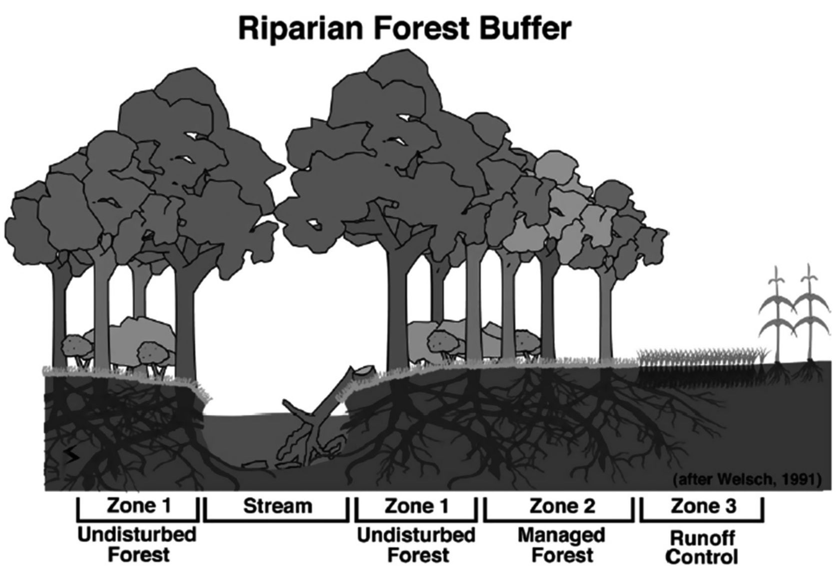

Figure 1 The traditional three-zone riparian buffer. Source: reprinted with permission from Schultz et al. (2004) by American Society of Agronomy.

Table 1 Functions of the grass, shrub and tree components of riparian buffers

Kind of plant	Functions
Prairie grasses/forbs	1. Slow water entering the buffer
	2. Trap sediment and associated chemicals
	3. Add organic carbon to a range of soil depth
	4. Added carbon improves soil structure
	5. Improve infiltration capacity of the surface soil
	6. Above-ground nutrient sink needs annual harvest
	7. Provide diverse wildlife habitat
	8. Do not significantly shade the stream channel
	9. Provide only fine organic matter input to stream
	10. Can provide forage and other products
Shrubs	1. Multiple stems act as a trap for flood debris
	2. Provide woody roots for bank stabilization
	3. Litter fall helps improve surface soil quality
	4. Above-ground nutrient sink needs occasional harvest
	5. Adds vertical structure for wildlife habitat
	6. Do not significantly shade the stream channel
	7. Provide only fine organic matter input to stream
	8. Can provide ornamental products and berries
Trees	1. Strong, deep woody roots stabilize banks
	2. Litter fall helps improve surface soil quality
	3. Long-lived, large nutrient sink needs infrequent harvest
	4. Adds vertical structure for wildlife habitat
	5. Vertical structure may inhibit buffer use by grassland birds
	6. Shade stream, lowering temperature and stabilizing dissolved oxygen
	7. Provide both fine organic matter and large woody debris to the channel
	8. Can provide a wide variety of fibre products

The reason is that if the streambank is completely shaded, grasses needed to stabilize the bank will be difficult to establish and grow and bank erosion will continue with the chance that trees could fall into the channel creating problems. If, however, streams are large enough and there is a desire to create natural in-stream habitat, trees could be placed closer to the bank so that some large mature trees could fall into the channel to provide large woody debris that helps create important pool and woody in-stream habitat for a myriad of organisms. For this to happen, trees in Zone 1 would not be harvested during their life time. If in-stream large woody debris is not desired because of concern for development of log dams and increased water levels harvesting with replacement would need to be done.

Tree spacing in Zone 1 should also be wide enough to allow grass or some other kind of cover crop to grow under the trees. If that does not happen, bare soil will exist under the trees after the litter from the previous fall leaf drop has either decomposed or been washed into the stream by surface run-off or by floodwaters from out-of-bank stream flow. This is an important consideration since the riparian buffer has been designed to slow surface run-off by providing a frictional surface of plants completely covering the soil. If there is no permanent ground cover under the trees, soil erosion and even gullies will develop carrying sediment into the stream and weakening streambanks.

One other consideration for row spacing is the direction that the buffers run. Rows should be wider for tree and shrub rows that run east and west to allow a longer time for the sun to actually shine directly down to the soil level. Rows running north and south can be narrower because the sun shines down between the rows unimpeded by the shade from trees.

Species of trees to be planted in Zone 1 would depend on channel incision. If the channel is a natural channel that is in contact with its flood plain, meaning that flood events typically would occur once every 2–3 years, true riparian tree species should be selected because the water table in such a situation would be relatively close to the surface. If on the other hand the channel is deeply incised as happens in watersheds where flow regimes have changed because of land-use changes or climate change, both true riparian tree species and upland tree species could be planted. Upland species are often slower growing and longer-lived trees. Trees in this zone might also include fruit trees or even shrubs if there was a desire to provide a short-term income generating plant community. If the buffer was established with assistance from a government conservation programme, it may not be possible to sell harvested fruits until the enrolled programme has lapsed. Zone 1 is usually the widest zone occupying up to two-thirds of the width of the buffer.

Zone 2 combines planting of trees and shrubs. It both helps to manage floodwater and allows run-off to infiltrate or percolate into the soil so that waterborne nutrients or pollutants are absorbed and cleansed by the soil and vegetation. Zone 2 would be used if Zone 1 consisted of trees. Zone 2 would have several rows of shrubs again spaced far enough apart so that sunlight can reach the soil at least during part of the day.

These rows of multiple woody stems provide an important barrier for slowing floodwater that is moving out into the agricultural field and trapping debris brought by the floodwater. The debris may consist of a wide variety of objects including large woody debris that, if not trapped by the shrubs in Zone 2, would end up in the adjacent crop fields, physically damaging the crops and requiring time and money for the farmer to remove. The shrub species in this zone can consist of edible berries and/or decorative woody florals such as red osier dogwood and curly willow. These are valuable components of the floral and decorating industries and can thus provide the farmer with income. The shrubs in Zone 2 also can provide a significant wildlife benefit to the buffer especially in attracting birds that may be important in helping to control pests in the adjacent crop fields. Bird species that are attracted to the shrub zone can be manipulated through the selection of shrub species that are planted.

Zone 3 is the zone adjacent to the crop field and the most important of the three zones. The zone is designed to provide high infiltration, sediment trapping and nutrient uptake ability while also dispersing any concentrated flow that runs into it. Native grasses and forbs provide the best buffering. They help to restore biological and physical soil quality to heavily used soils by adding large amounts of carbon to the profile from rapid turnover of roots that contain more than 70% of the total biomass of native prairie plant communities. This carbon plays a key role in redeveloping soil macro-aggregate structure that helps facilitate the high infiltration rates needed to get surface run-off into the soil profile. The carbon also serves as a substrate for increased soil microbial activity that is important both in building soil structure and processing some agricultural chemicals that move in the surface and groundwater (Dornbush et al., 2008).

Cool-season grasses are good at protecting the soil because, when water runs through the filter, they lie down, allowing the water to run over them and protecting the soil. However, they do not slow the flow of the water and are thus better adapted for use in grass waterways. Native grasses and forbs slow the water because their stiff stems seldom bend in response to surface run-off. This results in the majority of the sediment in surface run-off being dropped on the crop field at the edge of the buffer prior to the water moving through Zone 3. That sediment can be moved back upslope where it can be used by crops. The mix of native prairie grasses and forbs provides excellent habitat for prairie and forest edge wildlife such as pheasants and quail. In regions where hunting game is an activity, riparian buffers with a Zone 3 prairie strip and a Zone 2 shrub strip can provide excellent bird hunting opportunities that some landowners lease to hunters.

If a crop field has more than a 5–8% slope, a pure switch grass (*Panicum virgatum*) strip can be planted at the field edge of Zone 1 to slow the water. The deep rooting habit of the native prairie grasses and forbs creates a soil that has high infiltration rates. Even on soils that have been cultivated for many years and lost their surface soil structure, native prairie plants can recreate soil structure and porosity similar to that of the original undisturbed soil in 8–10 years (Marquez et al., 2004, 2019). Cool-season grasses such as fescue and brome take a significantly longer time to improve infiltration rates to the same depth as under a native plant buffer community.

Planning considerations during buffer design should include a strong focus on the landowners' desires and objectives while also retaining the buffer's ability to provide critical environmental benefits and services. Buffers designed for stabilizing collapsing streambanks in deeply incised channels should have the first rows of trees set back far enough from the edge of the bank to allow grass or other dense ground cover to grow both above and on the bank in full sunlight. In such cases, trees that have a propensity for producing large major roots with many smaller fibrous roots should be selected as these species' root systems can provide the reinforcing structures that hold the banks in place. Buffers designed to maximize capture and filtration of crop field surface run-off should consist of native prairie grasses and forbs that provide stiff stems to slow water at the field edge of the buffer, dropping much of the sediment and then providing high infiltration rates to significant depths that allow the potentially nutrient laden water to be filtered through an active plant community root system.

4 Special design considerations and management

Design guidelines and planning tools for riparian forest buffers are provided by Bentrup (2008) and MacFarland (2017). While it is relatively straightforward to design a three-zone riparian buffer based on the above standard design, it is critical to fit that buffer to the actual landscape which often requires additional conservation practices that must be integrated with the buffer to make the system function to its maximum potential. To accomplish this integration of various potential conservation practices, design planning should include an on-the-ground walk-through with the landowner as well as an aerial photograph of the site that shows other conservation practices such as grass waterways and other problem areas such as field drainage tiles, gullies and areas of severe bank erosion and collapse. Recent advances in remote sensing have the potential to help buffer zone planning and management significantly (Herring et al., 2006; Goetz, 2006). Techniques such as high-resolution imaging and laser-based techniques can provide detailed information on buffer zone properties such as topography, buffer length, width and vegetation structure as well as stream flow.

As mentioned earlier, where there is severe bank erosion, Zone 1 trees should be set back from the bank edge to allow enough sunlight to support the growth of dense grass or other cover on the bank. Shrubs could replace trees in the first row or two of Zone 1 to reduce the potential of shading the stream. This is an important consideration in some prairie landscapes where warm-water streams exist and lowering water temperature is not desired. Replacing the first row or two of trees with shrubs may also be appropriate where there is significant landowner concern about large woody debris falling into the stream which might raise water levels, thus backing up water into field drainage tiles.

If the region includes field drainage tiles such as those found on the Des Moines lobe and other recently glaciated regions in the Midwestern United States, a grass waterway of introduced cool-season grasses should be planted over the tile as it passes under the buffer unless the tile can be replaced by a section of solid tile that has no access holes or cracks that provide potential access to plant roots. The deep roots of the native plant community or of trees will access the field drainage tile and plug it to the point that it will no longer carry water from the wet areas of the upland crop field.

In areas where grass waterways from the upland intersect the riparian forest buffer, Zone 3 of the buffer should be expanded out into the crop field or at the expense of the other two buffer zones. Grass waterways are designed to carry surface run-off water safely downhill. When this fast-paced water approaches a buffer strip, it must be dramatically slowed to allow the water to infiltrate into the soil below the buffer. In such cases, Zone 3 should consist only of native grasses and forbs with a strip of native grasses without forbs right at the field edge of Zone 3. The grass waterway should be widened at the edge of the buffer, creating a pyramidal structure with the base against the buffer to allow water a place to slow and sit before it moves through Zone 3.

Buffer widths can vary depending on space available, soil and slope conditions and landowner objectives (Fig. 2). Dosskey et al. (2015) have developed AgBufferBuilder, a GIS tool to design buffer strips using digital elevation models and buffer area ratio relationships, to develop buffers that have a constant level of trapping efficiency along the extent of the buffer. Riparian buffers as narrow as 10–15 m can provide surface erosion control, but nitrogen (N) reduction in subsurface flow may require widths of 30–46 m depending on the soil type and the slope of the riparian zone. When working with the landowner, it is important to determine the number of up and down field passes a field operative can make with the equipment available. In a rectangular field, buffer widths should allow the farmer to end tillage and harvesting passes up and down field in a way that will bring them back to the end of the field that they use for access to the field. If the stream meanders along the edge of the field, the buffer will need to vary in width to create the rectangular shape of the field.

The length of a riparian buffer system should ideally include both sides of the channel beginning in the headwaters of the watershed and extending continuously as far downstream as possible. Natural buffers can be part of the total length of a buffer system as long as they fall within the required widths needed to capture surface run-off and reduce the nutrient content of the subsurface flow to the channel. Leaving significant lengths of the channel without riparian buffers or some other kind of perennial cover can actually

Figure 2 A riparian buffer applied to the landscape. Note the variation in width of Zone 3, the native grass and forb zone, to fit the landowners' objectives. Also note the gentle smooth edge of Zone 3 along the buffer to allow ease of cultivation with large equipment.

create more problems for channel stability. If bank collapse takes place along unbuffered reaches of the channel, channel widths increase in that zone which causes water depths in the channel to decrease until the water hits a narrow channel that is stable because it is buffered. The turbulence caused by forcing the water into a narrower channel can increase undercutting and scouring along the buffered bank, causing it to collapse especially if the riparian buffer is relatively young.

Long-term management of the buffer is required to maintain its design functionality. No grazing should be allowed in Zones 1 and 2. If properly managed, flash or rotational grazing in dry soil conditions can be undertaken in a Zone 3 sown with cool-season grass. Some harvesting could be done in Zone 1 if the species used are stump or root sprouting species. If they are root sprouting species, row definition will be lost and woody tree stems could sprout into the Zone 3 grasses and forbs because tree roots extend laterally away from the bole to an average distance of one tree height from the base. Berries and shrub stems, to be used for ornamental purposes, can be harvested from Zone 2. Zone 3 cool-season grass could be cut for hay once in the growing season – ideally done in the season with the least potential flooding. More importantly, if Zone 3 consists of native grasses and forbs, it must be burned every 3–5 years to maintain the biodiversity of the plant community. If that is not done, invasive weeds or grasses, such as reed canary grass (*Phalaris arundinacea*), will find their way into the zone over time.

Riparian forest buffers may need to be used in conjunction with other riparian management practices such as streambank bioengineering, in-stream boulder weirs or constructed wetlands. Both streambank bioengineering and in-stream boulder weirs (Fig. 3) are designed to stabilize the channel by creating steps in the channel evolution process. In-stream boulder weirs are designed to slow down-cutting in the channel by creating a series of weirs in the channel with 1:4 slopes upstream of a series of cross-channel crest stones, and 1:20 slopes of rock downstream of the crest stones. Weirs are placed so that the upstream pool behind the crest stones of one weir are backed-up to the gentle downstream side of the weir upstream of that weir during base-flow. The goal is to reduce down-cutting and pool development downstream of the weir crest stones.

Streambank bioengineering is designed to stabilize eroding streambanks usually associated with a channel that needs to adjust to changes in discharge.

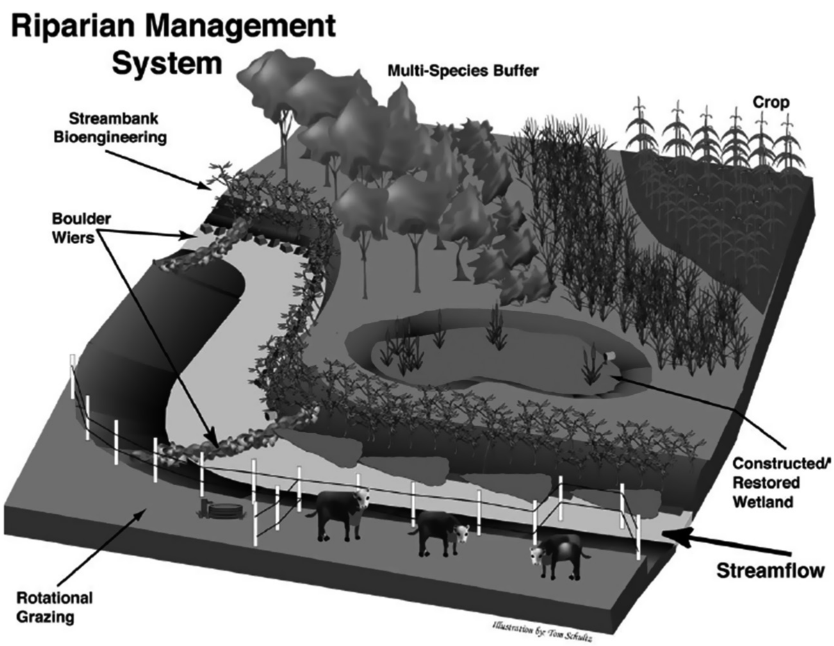

Figure 3 Riparian management system practices including from top right: streambank bioengineering, in-stream boulder weir structures, intensive rotational grazing, constructed wetlands and riparian forest buffer that could also be designed as a saturated buffer. Source: reprinted with permission from Schultz et al. (2004) by American Society of Agronomy.

Channels that are down-cutting, with the streambanks being taller than can be supported by the bank soil or parent material, can result in the banks collapsing, thus widening the channel. Bioengineering techniques include use of both hard engineering materials such as boulders for toe control and grasses and woody cuttings placed into the bank wall (Figs. 4 and 5).

Figure 4 Streambank bioengineering on streambanks that were severely eroded. Bear Creek in Central Iowa, USA – A USDA National Research and Demonstration Site – 1998.

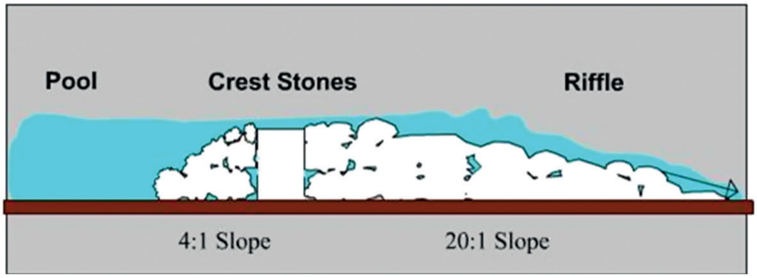

Figure 5 Boulder weir to control channel down-cutting by having a long gentle slope on the downstream side of the structure. Crest stones should be large stones that in the top layer allow fish to move over the crest. Boulder weirs are installed in a sequence with the upstream pool of the downstream weir backing water up to the long, gentle downstream rock sequence at base-flow conditions.

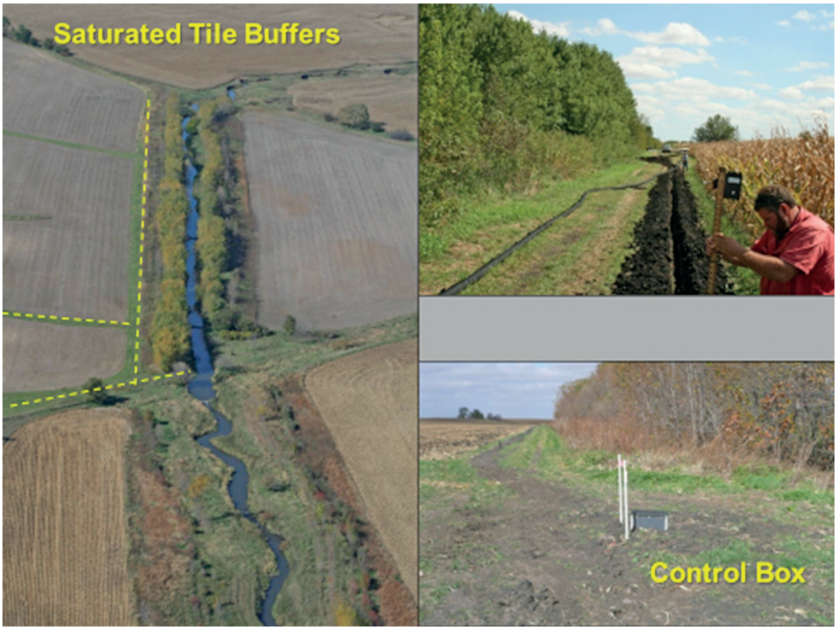

Figure 6 Saturated buffer. Field drain tile that intercepts tiles from upslope is laid parallel to the buffer. Water from the parallel tile now moves through the buffer instead of directly into the channel without any plant/soil treatment of the nutrient load.

Saturated riparian buffers are a relatively new addition to the buffer portfolio (Fig. 6). In this practice, a field tile that intercepts field tile draining upslope areas is laid parallel to the field edge of the buffer (Jaynes and Isenhart, 2014). Water flowing into this tile moves out of the tile and through the riparian buffer subjecting it to the treatment of the soil and plant community. Nitrate reduction is as high as 90% in the water flowing through the buffer before reaching the stream.

Streamside buffers cannot remove materials from field drainage tiles that exit directly into a stream. But an acre of tile-intercepting wetland has been calculated to remove from 20 to 40 tons of N over a period of 60 years. Likewise, creating saturated buffers with field tile that is laid parallel to the field side of the buffer and intercepts field tile that drains the adjacent field can reduce the nitrate content by 90% (Jaynes and Isenhart, 2014).

5 Assessing buffer performance

Tracer tests and isotope evidence shows that denitrification is the major groundwater nitrate removal mechanism in the buffer system (Schultz et al., 2004). Stratigraphy below buffers can determine the effectiveness of nutrient removal from shallow groundwater. With a shallow confining layer of till below a loamy root zone, buffers can remove up to 90% of the nitrate in groundwater. When the confining layer is found well below the rooting zone and porous sand and gravel are found between the till and the loam, residence time and contact with roots is dramatically reduced and buffers are unable to remove much nitrate from the groundwater. The difficulty in describing the stratigraphy below buffers makes it difficult to quantify the specific amount of remediation that a planned buffer might provide. To be able to measure in-stream water quality improvement, continuous buffers on both sides of the stream must extend at least 15 km.

Studies that have been conducted on the riparian forest buffers in the Bear Creek Watershed located on the Des Moines Lobe in Central Iowa in the United States have shown that a 7-m wide native grass filter strip on either side of the stream can reduce sediment loss to the stream by 95% and total nitrogen, phosphorous and nitrate and phosphate in the surface water by 60% (Schultz et al., 2004). This research suggests that adding a 9-m wide woody buffer to the grass filter results in removal of 97% of the sediment and 80% of the nutrients. There is also a 20% increase in removal of soluble nutrients with the added width (Simpkins et al., 2003; Lee et al., 2000, 2003). Riparian forest buffers can reach maximum efficiency for sediment removal in as little as 5 years and nutrient removal in as little as 10–15 years. Water can infiltrate in the soil up to five times faster in restored buffers in as little as 6 years after establishment compared to adjacent crop fields. Riparian buffer strips also have been shown to retain between 79% and 94% of the atrazine in run off from adjacent crop fields (Reungsang et al., 2005).

In terms of soil stability, it has been shown that buffered streambanks lose up to 80% less soil than row cropped or heavily grazed streambanks (Zaimes et al., 2004; Marquez et al., 2004). A study in the Central Claypan area of northeastern Missouri found that at the watershed scale, streambank erosion accounted for an average of 88% of the in-stream sediment and 23% of the N load on an annual basis suggesting the importance of using perennial vegetation to stabilize streambanks (Willett et al., 2012). Soils in riparian forest buffers contain up to 66% more total organic carbon in the top 50 cm than adjacent crop field soils (Tufekcioglu et al., 2003). *Populus* hybrids and switchgrass living and dead biomass sequester 3000 and 800 kg C ha^{-1} and immobilize 37 and 16 kg N ha^{-1}, respectively. Riparian forest buffers have more than eight times more below ground biomass than adjacent crop fields. Buffer soils show a 2.5-fold increase in soil microbial biomass and a fourfold increase in denitrification in the surface 50 cm of soil when compared with the adjacent crop field soil.

Bird species' use of buffers has shown that riparian forest buffers with a three-zone system of trees, shrubs and native grasses which provide a variety of habitat structure will support over 40 different bird species over the year in central Iowa compared to 8–10 species in non-buffer agricultural riparian zones with row crop culture to within 5 m of the channel (Berges et al., 2010). If properly designed, riparian buffers can protect a stream from chemical and sediment pollution while providing both terrestrial and aquatic wildlife habitat in agricultural landscapes that are dedicated to producing annual crops to feed humans and livestock or to create biofuels that replace fossil fuels.

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Index